sensor offset, humidity sensor offset, heating and cooling coil fouling, and dirty air filters. Additional effort is still needed to expand the fault simulation such as water temperature sensor fault.

Second, multiple fault intensity levels are rarely analyzed. Most of the existing studies focused on one or two fault intensity levels. More quantitative analysis of different fault intensity levels is needed.

Third, the impact of equipment fault depends on the building energy system and its control system, but existing simulation models typically do not capture all control sequence elements. Some modeling tools can only provide approximate estimates of the potential impact of faults. For example, the performance of static pressure reset sequences may be affected by the health state of VAV dampers, air resistance at duct network, and supply/return fan performance curves. Therefore, such effects cannot be captured by simulation tools where duct pressure modeling is abstracted out.

In this manuscript, we present a model-based approach to fault impact analysis that addresses the limitations highlighted above. Herein we use co-simulation between EnergyPlus and Modelica to develop a virtual testbed based on modeling a large commercial building served by a VAV-based system.

This virtual testbed can be used to evaluate and analyze the impact of single or multiple faults at various fault intensity levels. Furthermore, the testbed can be used to generate representative simulated data for testing performance of fault detection and diagnosis methods.

This paper is organized as follows: Section 2 describes the fault modeling, the virtual testbed and its fault insertion capability, and evaluation metrics for fault impact analysis. Section 3 explains the simulation method and scenarios design for fault impact analysis. Section 4 includes several examples of using the virtual testbed to conduct a fault impact assessment study on the HVAC system in a large commercial building model. The conclusion section includes discussion of future research.

VIRTUAL TESTBED, FAULT MODELING AND PERFORMANCE METRICS

Our approach is to use a dynamic simulation platform (a virtual testbed) to assess the fault impacts of two main scenarios: 1) fault onset from normal condition, and 2) continuous faulty scenario. This section introduces the testbed, fault modeling, and performance evaluation metrics, and fault onset data generation. First, we approximate the occurrence of fault by mathematic representation for simulation purpose fault formulation. Second, we implement such fault model in the simulation platform (virtual building). Third, we design specific simulation scenarios. Considering the dynamic performance and long-term performance of a control system, simulation scenarios are typically selected from two aspects of evaluations, quantitative long-term (week / month /year) impacts, and chronological short-time (within hours) dynamic impacts, which can be also used to generate a fault onset data set for FDD method testing. The following further explains the details of each step.

Virtual testbed and fault insertion capability

To simulate the fault, we use a dynamic co-simulation framework, consisting of the EnergyPlus model for the building envelope and thermal load and the Modelica model for the HVAC system. Specifically, we select a large office building as the primary focus because this building type represents the largest floorspace among all commercial building types in U.S. based on 2012 Commercial Buildings Energy Consumption Survey Data (U.S. EIA 2016). For modeling, we primarily use the U.S. Department of Energy large office reference model developed by Deru et al. (2011) to capture the envelope characteristics and the associated building load. The large office building model has twelve floors and each floor has five thermal zones, i.e., east, south, west, north, and core zones. The building has a single duct multi-zone HVAC system (shown in Figure 1), served by chilled water loop and hot water loop. Each zone is served by the VAV box with water-based reheat coil. Such an HVAC system configuration is representative of, and is commonly found in large office buildings across the States. To model dynamics of the HVAC system and control sequences, we use Modelica Buildings library developed by Wetter et al. (2014) and also develop new component models.

This co-simulation framework can simulate the performance of building thermal dynamics as well as the immediate control response for a given control baseline. The control baseline used in this study is assumed to represent a typical existing building, and is composed of specific control sequences for each HVAC actuator and systems. The control baseline is defined based on representing the majority of existing building stocks, following the control specification from ASHRAE 90.1-1989, 90.1-1999. It has a fixed control setpoint for supply and return fan, outdoor air damper, and supply air temperature setpoint (shown in Table 1). We assume this represents the typical control sequences in existing commercial buildings. More details of the HVAC configurations and co-simulation setup can be found in Huang et al. (2018). Hardware faults are simulated in addition to the normal operational model as an overwrite process. Figure 1 illustrates the fault insertion capability for this simulation model. This includes all the temperature sensors, airflow sensors, humidity sensors, occupancy sensors, cooling coil valves, heating coil valves, and dampers. This capability can be easily ex-

For each simulation scenario, we first generated the data set using the simulation model, then analyzed the data for fault onset impact and long-term impact assessment as discussed in the following section.

DISCUSSION AND RESULT ANALYSIS

Week-long impact analysis

The results for long-term impact analysis include three scenarios: the supply air temperature sensor bias, outdoor air temperature sensor bias, and the cooling coil valve stuck. As the fault intensity varies, their impacts on energy and comfort also vary.

For the outdoor air temperature sensor bias (shown in Figure 2), negative bias increases its economizer-enabling status, and increases thermal discomfort, while decreasing electrical energy consumption. Positive bias decreases economizer enabling status, decreases gas energy consumption, and decreases thermal discomfort, while increasing electrical energy consumption.

For the fault of supply air temperature sensor bias (shown in Figure 3), negative bias decreases both gas and electrical energy consumption, while decreasing thermal comfort. The positive bias increases both the gas and electrical energy consumption, while slightly increasing thermal comfort.

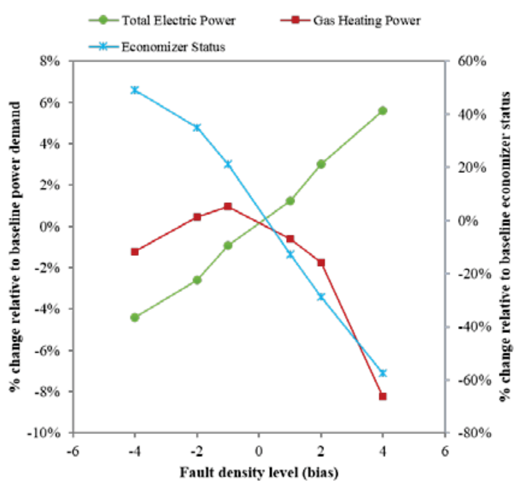

Figure 2: Week-long (May 7-14) total energy and operation impact of outdoor air temperature sensor bias at different fault intensity levels

For the cooling coil valve stuck (shown in Figure 4), because the valve typically opens around 10% under no-fault scenario in the selected simulation case, as the valve fault intensity varies: 1) Valve stuck (larger than 10%) will result in an energy usage increase; the larger the valve stuck position is, the more energy will be wasted; 2) valve stuck on smaller opening (e.g., 0%) will result in energy reduction. However, the zone temperature setpoint cannot be met (significant thermal discomfort), because of insufficient cooling capacity.

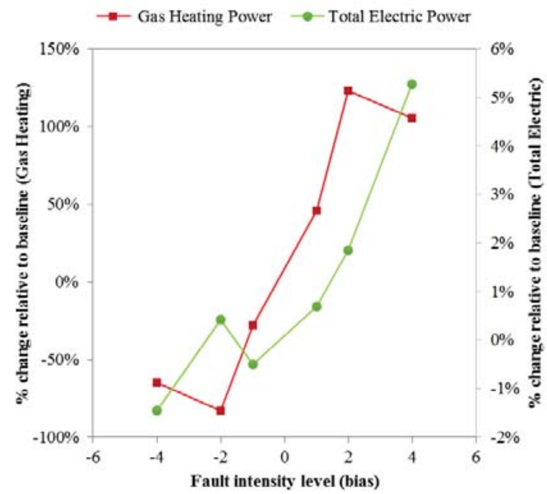

Figure 3: Week-long (August 6-13) impact of supply air temperature sensor bias at different fault intensity levels

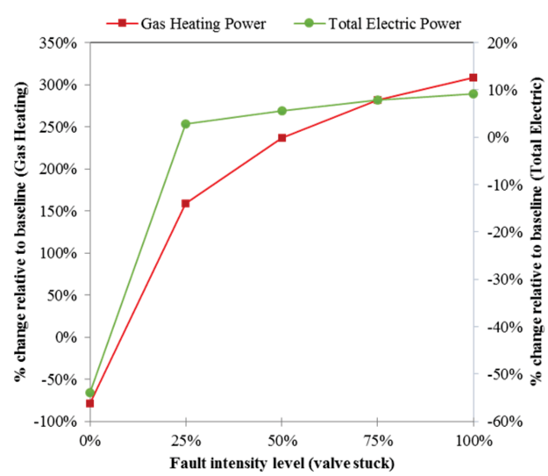

Figure 4: Week-long (August 6-13) impact of cooling coil valve stuck at different fault intensity levels

Fault onset impact analysis

Results from three fault scenarios are shown below. We use the same baseline scenario with no fault injection (shown in solid green line in Figures 5-7). The other plotted data (shown in red round dots and brown square dots in Figures 5-7) are simulated with one or two faults in-

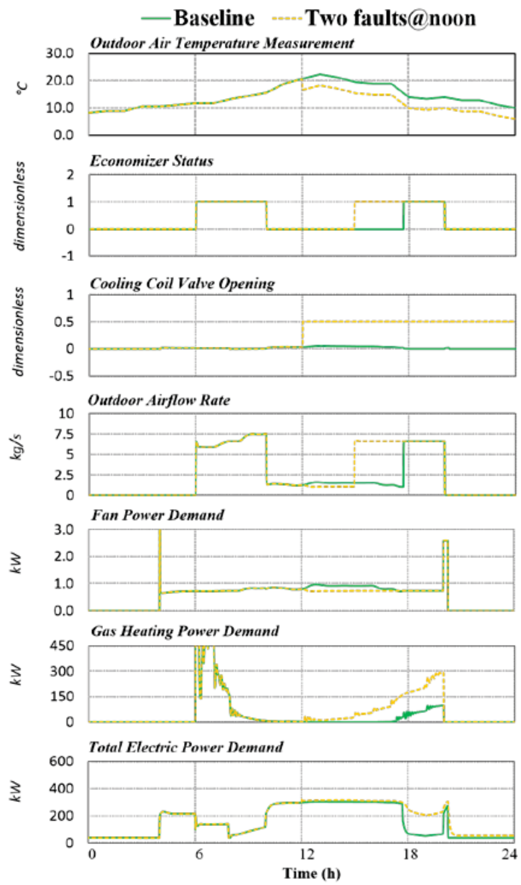

Figure 7: Impact of outdoor air temperature sensor bias and cooling coil valve stuck inserted at 12pm on system operation and power consumption

water flow, and reduces the supply air temperature. Then, it reduces the fan speed and reduces the zone temperature. As a result, it increases heating power demand for reheat and increases total electric power demand.

Simulated scenario (c): Cooling coil valve gets stuck (50% open) and outdoor temperature sensor bias (-4°C) on May 10, at 12:00 pm. Dynamic impact (shown in Figure 7): Comparing to the individual fault onset analysis, combination of the two faults has some similarity from each of the separate fault onset scenarios. However, the separate impacts don't simply sum up because the system is non-linear.

From the result and analysis above, we found the following characteristics for the transient impact of faults:

- Each fault disrupts the normal operation of HVAC components at different time periods depending on the control event. The impact of sensor or actuator faults might be either immediate or manifest in the future depending on the implemented control sequence and system operating conditions.
- In general, a larger fault intensity leads to a larger impact on system performance; and the impact magnitude is nonlinearly correlated with the fault intensity.

These characteristics are related to the thermal inertia for building envelope and environment, a relatively slow actuation process in HVAC system and components, and complex interactions between different control loops.

Table 3 summarizes the findings for both fault onset and fault long-term impact analysis. We believe the analysis presented in this paper not only provides a starting point for further evaluation and fault impact analysis, but also provides insights on how the fault occurrence affects the operation of the HVAC system and that of HVAC equipment.

CONCLUSION

Physical faults can affect building operation at various levels depending on several factors, including fault type, fault intensity level, operational status, and weather. This paper described a simulation-based approach to fault impact analysis on a single duct VAV system. The use of a virtual testbed enabled us to quantitatively evaluate the impact of simulated physical faults on the energy, comfort, and operational performance for different fault intensity levels and under different weather conditions.

The use of this virtual testbed allows for quantifying the potential long-term impact of different faults this way, enabling maintenance schedule definition to minimize the cost of building operation. Furthermore the virtual testbed can be used in the process of developing and testing fault detection and diagnosis algorithms to test the efficacy of these tools in different operating conditions and in conjunction with specific control sequences.

Predictive analytics focused on estimating remaining useful life of equipment have been developed and are a common practice in other industries with reliability driven business models. Such algorithms have not been used for HVAC and the building systems industry. Future research will investigate topics such as prediction of fault occurrence time, based on analysis of equipment health state indicators. In this way, the fault impact can be eliminated by taking remedial actions prior to fault occurrence.

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Table 3: Summary of fault impact result analysis.

Impact Analysis	**Hardware Type**	**Fault Type**	**Generic Findings**	**Specific Findings**
Fault onset	Outdoor air temperature sensor	Bias	The onset of fault affects relevant HVAC components sequentially based on the control logic flow. Impact of multiple faults are not linearly added up.	Fault −→ economizer enabling −→ mixing box control, fan control, and cooling demand.
	Cooling coil valve	Stuck		Fault −→ chilled water flow −→supply air temperature control, fan control, and VAV box reheat control.
	OA sensor fault and cooling coil valve fault	Bias		Fault −→ chilled water flow−→ economizer enabling −→mixing box control, supply air temperature control, fan control, and VAV box reheat control.
Long-term fault	Outdoor air temperature sensor	Bias	The impact of hardware fault varies with fault intensity, fault types, and hardware types. These faults typically affect energy or thermal comfort, or both. They tend to reduce energy with increased thermal discomfort, or purely increase energy usage.	temperature sensor \, economizer usage /total energy usage \, thermal discomfort /; Vice versa.
	Supply air temperature sensor	Bias		temperature sensor \, total energy usage \, thermal discomfort /; Vice versa.
	Cooling coil valve	Stuck		Valve stuck at smaller position \, total energy usage \, thermal discomfort /; Vice versa.

Meaning of symbols: −→affect, / increase, \, decrease

REFERENCES

Beghi, A., R. Brignoli, L. Cecchinato, G. Menegazzo, M. Rampazzo, and F. Simmini. 2016. "Data-driven Fault Detection and Diagnosis for HVAC water chillers." *Control Engineering Practice* 53:79–91.

Breuker, M., and J. Braun. 1998. "Common Faults and Their Impacts for Rooftop Air Conditioners." *HVAC&R Research* 4 (3): 303–318.

Deru, M., K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, and M. Rosenberg. 2011. "U.S. Department of Energy commercial reference building models of the national building stock." NREL Report No. TP-5500-46861.

Fernandez, N., S. Katipamula, W. Wang, Y. Xie, and M. Zhao. 2017. "Energy savings potential from improved building controls for the US commercial building sector." *Energy Efficiency*, pp. 1–21.

Granderson, J., R. Singla, E. Mayhorn, P. Ehrlich, D. Vrabie, and S. Frank. 2017. "Characterization and survey of automated fault detection and diagnostics tools." 11/2017.

Huang, S, Y. Chen, D. Vrabie, and P. Ehrlich. 2018. "A control-oriented building envelope and HVAC system simulation model for a typical large office building." *2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA*, September 26-28, Chicago, IL.

Hyvarinen, J, and S. Karki. 1996. "Building optimization and fault diagnosis source book." *IEA Annex 25*, no. 1996.8.

Lee, S.H., and F.W.H. Yik. 2010. "A study on the energy penalty of various air-side system faults in buildings." *Energy and Buildings* 42 (1): 2–10.

Qin, J., and S. Wang. 2005. "A fault detection and diagnosis strategy of VAV air-conditioning systems for improved energy and control performances." *Energy and buildings* 37 (10): 1035–1048.

Roth, K.W., D. Westphalen, M.Y. Feng, P. Llana, and L. Quartararo. 2005. "Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential." Report, TIAX LLC.

Schein, J., and S. Bushby. 2006. "A Hierarchical Rule-Based Fault Detection and Diagnostic Method for HVAC Systems." *HVAC&R Research,* 12 (1): 111–125.

Seem, J.E., J.M. House, and R.H. Monroe. 1999. "On-line monitoring and fault detection." *ASHRAE journal* 41 (7): 21–26.

U.S. EIA. 2016. 2012 Commercial Buildings Energy Consumption Survey (CBECS) Survey Data. Accessed on August 8, 2017.

Wang, S. W., and F. Xiao. 2004. "AHU sensor fault diagnosis using principal component analysis method." *Energy and Buildings* 36 (2): 147–160.

Wetter, M., W. Zuo, T. Nouidui, and X. Pang. 2014. "Modelica Buildings library." *Journal of Building Performance Simulation* 7 (4): 253–270.

Zhang, R. P., and T. Z. Hong. 2017. "Modeling of HVAC operational faults in building performance simulation." *Applied Energy* 202:178–188.