MODEL BASED FAILURE MODE EFFECT ANALYSIS ON WHOLE BUILDING ENERGY PERFORMANCE

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ABSTRACT

It is a known fact that fault in the buildings can cause as much as 30% increase in energy consumption. Thus, identifying critical failure modes affecting building energy performance is important. It can lead to actions to eliminate them, but it could as well play a role in designing a suitable monitoring and diagnostic system. Typically, expert judgment is used to guess critical faults, which leads to over instrumented, complex, and expensive building performance monitoring and diagnostic systems. In this paper, we demonstrate the application of Building performance simulation (BPS) tools to perform failure mode effect analysis and also propose a systematic process to identify and prioritize critical faults.

BPS tools can play significant role in facilitating energy retrofit analysis, supporting retro-commissioning activities and act as design support tool for sensor network to be used for continuous commissioning. However, current state of the art tools do not provide ability to model and simulate faults occurring in buildings. Thus, a readily deployable and generic fault modeling capability is required in order to take advantage of BPS tools for these applications. In this paper we present a building system fault modeling library developed in TRNSYS, a process for quantifying impact of individual as well as fault couplings and demonstrate both the process and the use of the fault library on a medium sized office building. The findings show that the fault coupling can boost the effect of faults that are individually not significant, which is not intuitive.

INTRODUCTION

It has been widely reported that degraded and poorly controlled building systems can use up to 30% more energy [Katipamula and Brambley 2005]. Building performance simulation (BPS) tools have become increasingly important with the growing strive to reduce energy use in building sector. Among other diverse applications, BPS tools can play significant role in facilitating energy retrofit analysis, supporting retro-commissioning activities and act as design support tool when designing sensor network to be used for continuous commissioning.

At the same time, current state of the art tools do not provide a standard and scalable capability to model and simulate faults occurring in buildings. With exception of few (e.g. EnergyPlus fault models [Basarkar et al. 2011]) BPS tools assume non faulty operation of the building system.

The objective of this paper is to develop a scalable model based approach for evaluating impact of various building faults, and extend it to prioritize building energy failure sources. Due to lack of scalable approach, expert judgment is currently used to guess critical building faults. Although this approach may work for handful of faults, it does not provide any quantitative measure of fault impact (e.g. kWh or $ wasted), and provides very little economic input for design of fault detection and diagnostics (FDD) system (i.e. does the fault impact warrant FDD system investment). Also, expert judgment typically fails to capture and prioritize coupling effect when multiple faults occur together. As we will show in this paper, coupling effect can be significant even though individually faults may be insignificant.

Thus, a readily deployable and generic fault modeling capability is required if BPS tools are to be employed in above mentioned applications. Also, a systematic process is needed to explore both individual and coupling fault impact. This was also a motivation behind the work reported in this paper. Our objective is to develop a generic model based approach that can be used for quantification of various faults and fault severities impact on energy consumption and develop a systematic process that uses this capability for fault prioritization. In this paper, we present a fault modeling library developed in TRNSYS and demonstrate its applicability in a systematic process for fault prioritization.

We note that although the library is demonstrated for fault prioritization at design stage in this paper, it has applications in other FDD areas as well, such as prognosis and real time fault impact assessment.

LITERATURE REVIEW

Building faults

There were a few attempts in the literature to provide lists of most common faults in building systems [e.g. ANNEX 25 1996, Lee et al. 1997, ASHRAE 1043-RP, (1999), Siegel (2002), Shun (2009).]. The faults could be of different types as reported by Haves (1977): abrupt – which happen suddenly, and degradation – which develop over time.

In this paper, we have derived an extensive list of different fault types AHU with VAVs and relevant building zones, based on in-house building expert brainstorming and Wen and Li (2011). Both abrupt and degradation faults were considered.

BPS for fault modeling

BPS tools have been increasingly used in building design. However, their use in operational phase has been restricted due number of limitations, one of which is their inabilities to directly account for imperfections in building systems that could possibly lead to misspredictions of performance.

Few isolated studies were reported in which BPS tools were used for fault simulation. Examples include: reverse control and leaky damper faults in HVACSIM+ by Dexter (1995), sensor offset and damper and valve mechanical blockage in MATLAB SIMULINK by Glass et al. (1995), cooling coil fouling and valve leakage in HVACSIM + by Haves et al. (1996) and economizer operation faults in DOE-2 by Katipamula et al. (1999). The faults were simulated perturbing relating parameters to mimic faults. Although this approach can lead to accurate prediction of the change in system performance, it heavily relies on expert judgments of the modeler and thus is not readily reusable for other buildings and available to other modelers. More reusable fault model developments in ENERGYPLUS have been reported by Basarkar et al. (2011).

In addition, the reported studies consider only individual fault effects on degradation of building performance. The coupling effect has not been part of above studies. As we show in this paper, building faults could show significant coupling effect when occurring simultaneously, which could as well cause difficulties in designing fault detection and diagnostic algorithms. Hence, a systematic approach to explore both individual and coupling faults is required, which is addressed in this paper.

FAULT MODEL LIBRARY

To simulate different faults, we developed a generic and scalable fault model library. Currently, the fault library is developed in TRNSYS (TRNSYS, v17), and is reusable and expandable to any building size (the fault types are listed in Figure 1). The library development resulted in a new TRNSYS environment. It is an extension of the commercially available tool that enables simulation of faults. TRNSYS graphical user interface is extended so, the faults can be modeled in TRNSYS Studio. We also developed a fault manager in TRNSYS, which is used to manage fault simulation and is also intended to serve as an interface to other simulation tools (such as optimization and/or uncertainty quantification tools).

The following inputs are needed to use the newly developed TRNSYS environment:

- TRNSYS textual input file (dck file);
- new TRNSYS environment (new .dlls and proformas in correct folders).

Although TRNSYS allows for high modeling flexibility, passing information from one component model to another without following the working fluid or signal flow is not recommended if consistency of fault propagation has to be assured.

The steps to simulate faults are as follows:

- import dck file into TRNSYS Studio;
- create (or Copy from 'Template') Fault Manager Component in the new TRNSYS project file;
- create links between Fault Manager and components in which faults are introduced;
- inject faults using the fault prioritization process discussed later run fault simulation.
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ECONOMIZER	PID CONTROLLER	HEATING COIL
OA DAMPER STUCK	UNSTABLE CONTROLLER	DIRTY COIL
RA DAMPER STUCK	INVERSE CONTROL	DAMPER STUCK
EA DAMPER STUCK	SET POINT OFFSET	DAMPER LEAKY
OA DAMPER LEAKY	STUCKACTUATOR	DAMPER OBSTRUCTED AT LOWER POSITION
RA DAMPER LEAKY	LEAKYACTUATOR	DAMPER OBSTRUCTED AT HIGHER POSITION
EA DAMPER LEAKY	ACTUATOR OBSTRUCTED HIGH	VALVE STUCK
AMBIENT AIR TEMPERATURE SENSOR OFFSET	ACTUATOR OBSTRUCTED LOW	VALVE LEAKY
COOLING COIL SET POINT TEMPERATURE OFFSET	MAX VALUE COMMISSIONED HIGH	VALVE OBSTRUCTED AT LOWER POSITION
ZONE TEMPERATURE SET POINT OFFSET	MAX VALUE COMMISSIONED LOW	VALVE OBSTRUCTED AT HIGHER POSITION
MIXED AIR TEMPERATURE SENSOR OFFSET	SENSOR READING OFFSET	
OA DAMPER OBSTRUCTED HIGH		
OA DAMPER OBSTRUCTED LOW		
MIN OA FRACTION OFFSET		

PLENUM	BOILER	DX COIL	SCHEDULE	FAN	PUMP
DUCT LEAK	BOILER REDUCED EFFICIENCY	SENSOR OFFSET	AMPLITUDE CHANGE	WORN/LOOSE FAN BELTS	MOTOR FAILING
DAMANGED INSULATION	BOILER REDUCED CAPACITY	REDUCED CAPACITY		INLET OBSTRUCTED	IMPELLER FAILING
	TEMPERATURE SENSOR READING OFFSET	REDUCED COP		24 HOUR OPERATION	INLET OBSTRUCTED
	OULTET AIR TEMPERATURE SET POINT OFFSET				

Figure 1: List of generic faults from the library

We identified three generic types of fault models (as illustrated in Table 1):

1. Continuous fault/ continuous variable: Fault where the transition from faulty to non-faulty state happens in continuous manner and which can take any value from a given continuous range (e.g. sensor temperature offset).

2. Discrete fault/ discrete variable: Fault where the transition from faulty to non-faulty state does not happen in continuous manner and which can only take value(s) from a discrete range (e.g. changing sign of proportional gain in PID controller).

3. Discrete fault/ continuous variable: Fault where the transition from faulty to non-faulty state does not happen in continuous manner and which can take any value from a given continuous range (e.g. actuator being stuck).

Table 1

Generic fault model types with illustrative examples

Continuous fault/ continuous variable	Discrete fault/ discrete variable	Discrete fault/ continuous variable
T_SET_ZONE= T_SET_ZONE+ FAULT	IF (FAULT.NE.0 .)THEN Kc=-Kc ENDIF	IF (FAULT.NE.0) THEN FRAC_OA=FAU LT ENDIF

In the current implementation of the library, each fault is represented by a single parameter (an example is given in Figure 2). The same parameter is used to indicate the presence of a fault, as well as to provide information about the intensity and characteristics of the fault. For all the parameters representing faults, value '0' specifies non faulty condition. Any other value is used to characterize the fault. This notion is natural for most of faults of the first type (Table 1) for which the change from faulty to non faulty condition happens by continuously changing a corresponding parameter. However, for the other two types, for which this transition is not, faulty condition is limited to values not-equal to '0'.

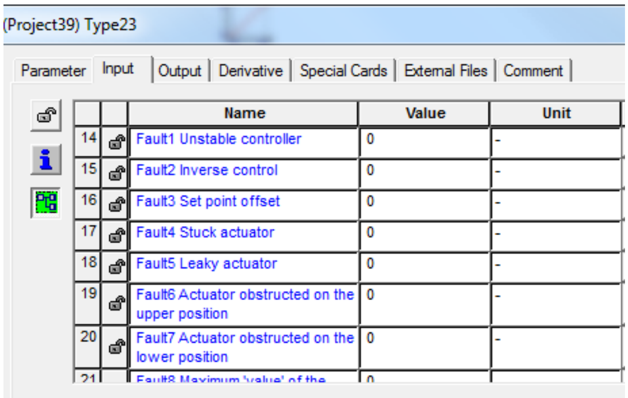

Figure 2: Integrated fault modelling interface

PROCESS FOR FAULT PRIORITIZATION

Figure 3 shows the process and the tool chain that we used for fault prioritization. The overall process involves use of a building model fault library as discussed in previous section. The list of faults to be evaluated and prioritized is based on those discussed in literature survey section, and any additional faults recommended by building energy experts. Next, we introduce all potential building faults one-at-a-time, and evaluate the building model to estimate building performance (whole building energy consumption in this study) under faulty conditions. This allows us to identify and prioritize key individual faults that are critical in terms of energy usage.

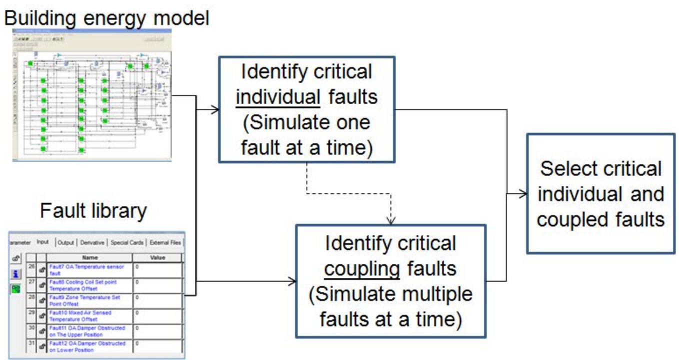

Figure 3: Overall process for fault prioritization

Next, we repeat the process with injection of two faults at a time. This helps us identify important couplings between different fault pairs.

Although not implemented in the current study, the process can be extended to evaluate coupling effect of multiple faults (i.e. more than two) as well. In our experience, available computational resource plays a key limitation, as the number of couplings grows exponentially. More sophisticated methods such as Sobol indices will be implemented in future to quantify higher order effect.

FAULT PRIORITIZATION: PERFORMANCE MEASURE

As stated earlier, we use the total impact of a fault on the whole building energy consumption as the performance measure to prioritize individual and couple fault effect. It is important to note that for the current study, we limited the analysis to a single performance indicator. Occupant comfort was not considered. Thus, in this study we do not differentiate between faults that could be detected by significant change in occupant comfort and those that could go undetected. Appropriate comfort measure can be used in the future to perform prioritization. Also, we assumed equal likelihood for all the faults in the current study. Figure 4 illustrates the performance measure defined for individual and couple faults.

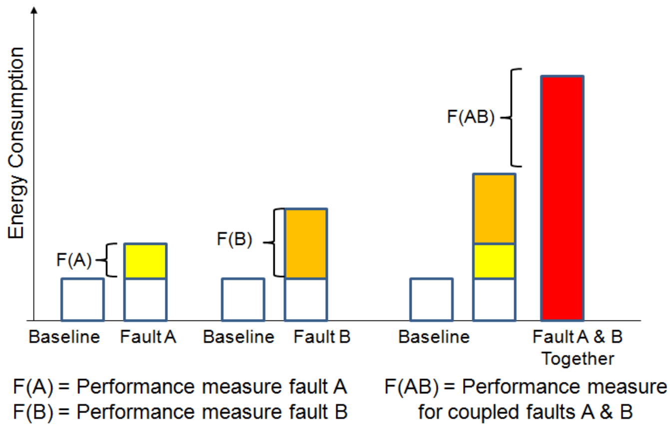

Figure 4: Performance measures defined for individual and coupled faults

Performance measure for individual fault prioritization is defined as a change in relevant building energy consumption when only one fault is introduced and is determined as follows:

F(A) = E(fault A introduced) – E(Baseline)

F(B) = E(fault B introduced) – E(Baseline),

where F stands for performance measure and E for energy consumption

Performance measure for fault coupling prioritization is defined as an additional change in building energy consumption over the additive change when two faults are introduced, and is determined as follows:

F(AB) = [E(faults A&B introduced) – E(Baseline)] – [F(A) + F(B)]

The fault prioritization is based on the impact on the above defined performance measures. The fault with higher performance measure is ranked higher. Same rationale is applied to coupling effect prioritization. Next, we illustrate out methodology with a case study.

DEMONSTRATION AND RESULTS

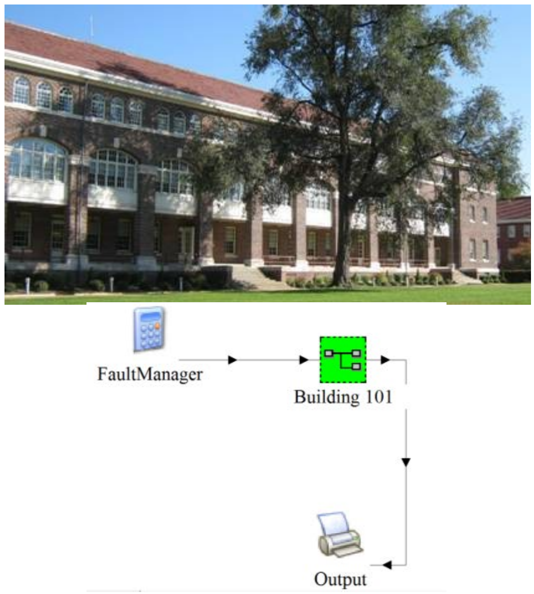

Figure 5: Building 101 and TRNSYS model

FAULT PRIORITIZATION IN SUMMER CONDITIONS

Figure 7 and Figure 8 (at the end of the paper) show the results of fault prioritization for summer conditions. For summer conditions, we used the building electric energy consumption as the performance measure. We can see from Figure 7 that 24 hour operation and OA damper stuck are top two faults, resulting in approximately 59% and 51% increase in electrical energy consumption, respectively. This result matches building experts' judgment/intuition. However, our methodology helped quantify the magnitude of energy impact of each fault, which is building system dependent and thus rarely intuitive. Knowledge of top individual faults is very useful to building energy manager, as either they can be eliminated or appropriate diagnostic packages can be deployed to monitor them. Also, the magnitude of the energy impact can also be used to perform economic assessment of such diagnostic package deployment.

As stated earlier, we evaluated the individual fault impact by injecting one fault at a time, followed by two faults (coupled faults) at a time evaluation. For simplicity, the time variation in fault intensities was not considered in this study even though the library does not pause such limitation. We simulated one week each from summer and winter seasons, and prioritized faults for each seasons. Next, we discuss the results from summer prioritization. For the discussion purposes, we only illustrate approximately top 15-20 faults in each category.

Figure 8 shows the prioritization of coupling faults, when two faults occur together. We point to an interesting result marked by red dotted oval. In summer, not shutting down the heating alone does not have significant impact on the performance measure. The same applies to having the heating water valve in AHU heating coil being stuck. However, if these two faults happen at the same time, their effect is significant.

For building 101, their coupled effect can be upwards of 20% increase in energy consumption. The heating will work against cooling and increase discharge air temperature from AHU. Occupant comfort does not necessary need to be decreased if it could be provided by higher air flow through each VAV. In Figure 6, we show a representative zone temperature during a week day. As it can be seen from the figure, the temperature does not rise above 26 degrees C. This means that the coupled faults' presence could be unnoticed by occupants and can have significant impact on degrading energy performance.

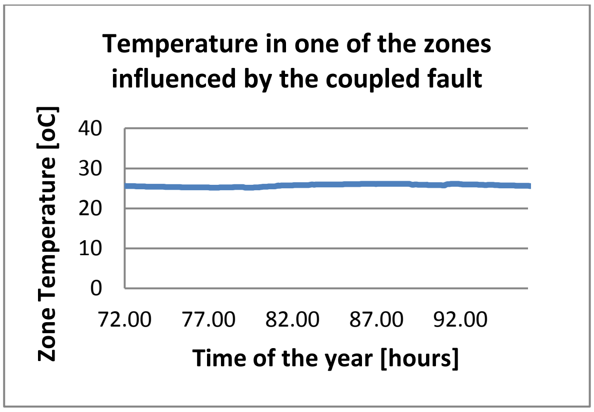

Figure 6: Temperature of a representative zone for the building under impact of the coupled faults

This result illustrates that the energy impacts estimated by our methodology for two faults occurring together are not as intuitive to the expert, as the individual faults. The methodology ensures that all key faults and couplings are captured, and nothing is left for intuition. Interestingly, the corrective action to suppress a coupling effect only involves fixing one of the faults. The energy manager can incorporate this information when prioritizing corrective actions.

FAULT PRIORITIZATION IN WINTER CONDITIONS

Fault Prioritization in Winter Conditions

Figure 9 (at the end of the paper) shows the results of fault prioritization for winter conditions, where we use the change in boiler thermal energy consumption as the performance measure. We can observe from Figure 9 that OA damper stuck is the top most fault for Building 101, resulting in approximately 400% energy consumption. Also, many other damper faults rank among top ten, e.g. damper obstructed and leaky.

In comparison to OA damper stuck, inverting the sign of the proportional gain (Kp) in PID control for AHU heating coil valve has negative impact on energy consumption. Under this fault, the energy consumption reduces by 35% (and therefore not seen in Figure 9). In addition, faults such as discharge air temperature (DAT) value offset and AHU heating coil valve being leaky, have only 20% increase above the baseline energy consumption. However, if any of the latter faults happen together with inverse Kp sign, the coupling impact energy increase to above 100% (Figure 10 at the end of the paper) over the baseline, which is very significant. As such, these coupling results are not intuitive as well, and demonstrate the benefit of our methodology.

In contrast with the summer example, the impact of these faults coupling on the occupant comfort is more pronounced. Because these couplings do impact the comfort, it is less likely that these faults will result in long-term degradation of energy performance in the building for the intensity of the faults chosen in the study (however, for lower faults' intensities, the impact to occupant comfort will be lower, while the energy performance degradation could still be high).

CONCLUDING REMARKS AND FUTURE WORK

In this paper, we developed and demonstrated that the fault library extends to BPS capability by enabling modeling and simulation of imperfections in the system in a well managed way (via fault manager). The added capability extends to both abrupt and degradation faults. Through systematic fault exploration process, we demonstrated that the coupling effect of faults can have significant effect on energy performance. Non-intuitive complex coupling effect of various faults has been demonstrated. The coupling effect can boost the effect of individual faults significantly.

The study was limited to second order interactions between the faults. The number of required simulations increases significantly for the higher order couplings. If higher order coupling effects are to be studied, a different simulation model would be preferred because TRNSYS is computationally demanding for such ventures. One way to alleviate this obstacle would be to develop reduced order model. Even though coupling effects could potentially have high impact on degradation of energy performance, their impact needs to be studied together with the probability of their concurrent occurrence to determine the real risks. Fault prioritization is only one of the potential applications of the fault library. In the future, this capability can be extended to other areas as well, such as fault prognosis during real time operation.

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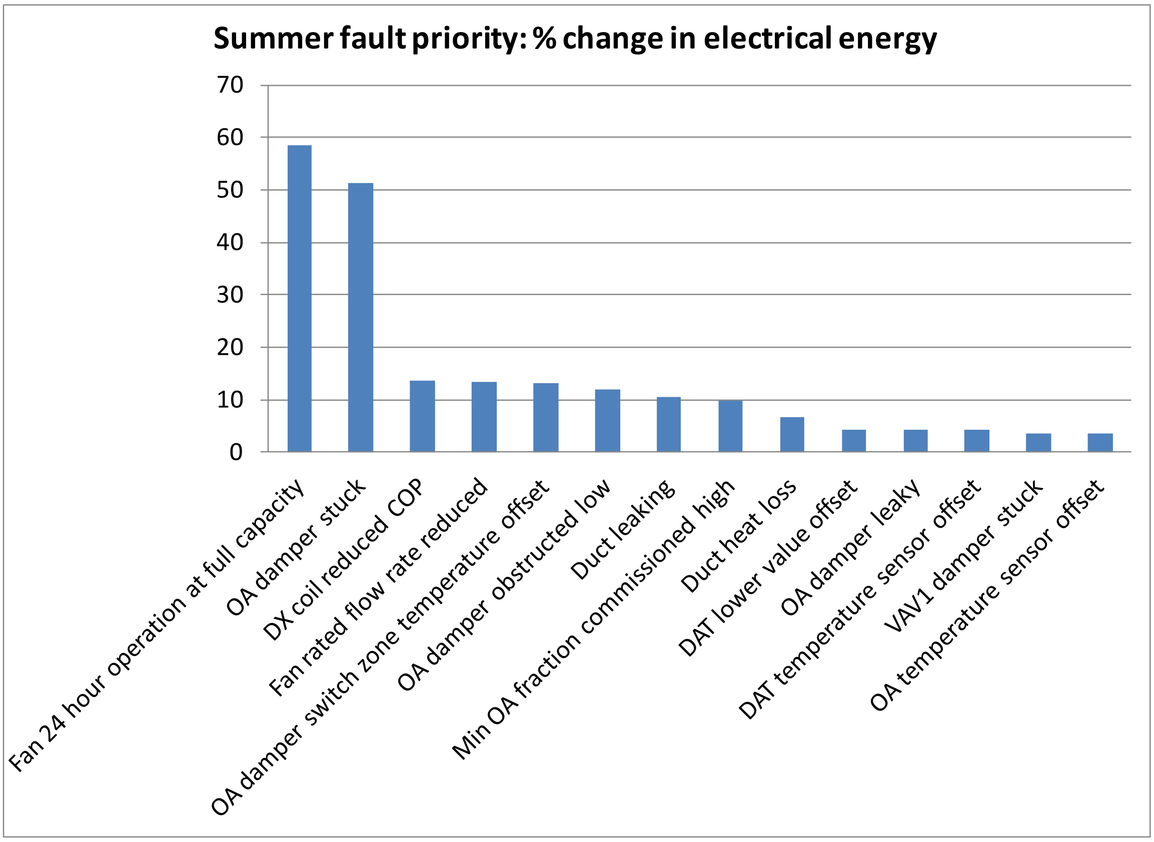

Figure 7: Individual fault prioritization for the summer week based on change in electrical energy (performance measure). Only top-ranked individual faults are shown.

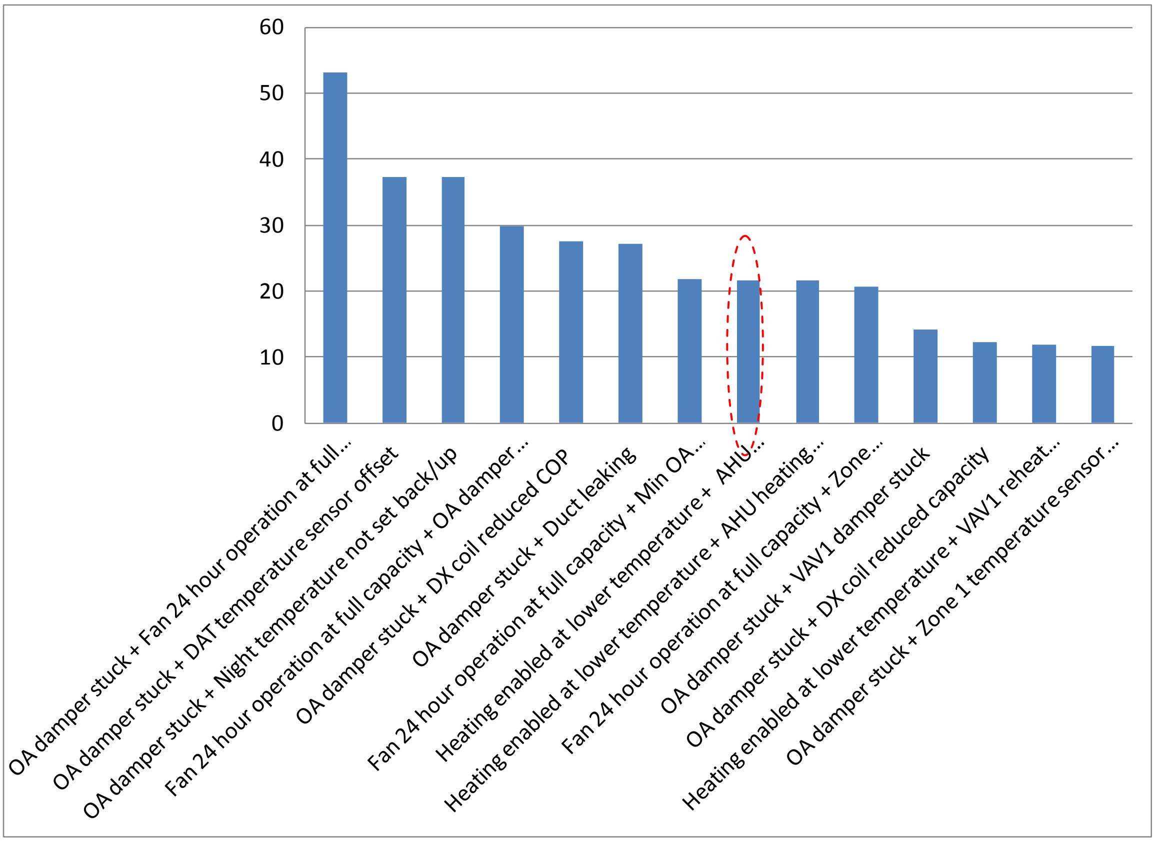

Figure 8: Fault coupling prioritization for the summer week based on change in electrical energy (performance measure). Only top-ranked fault couplings are shown.

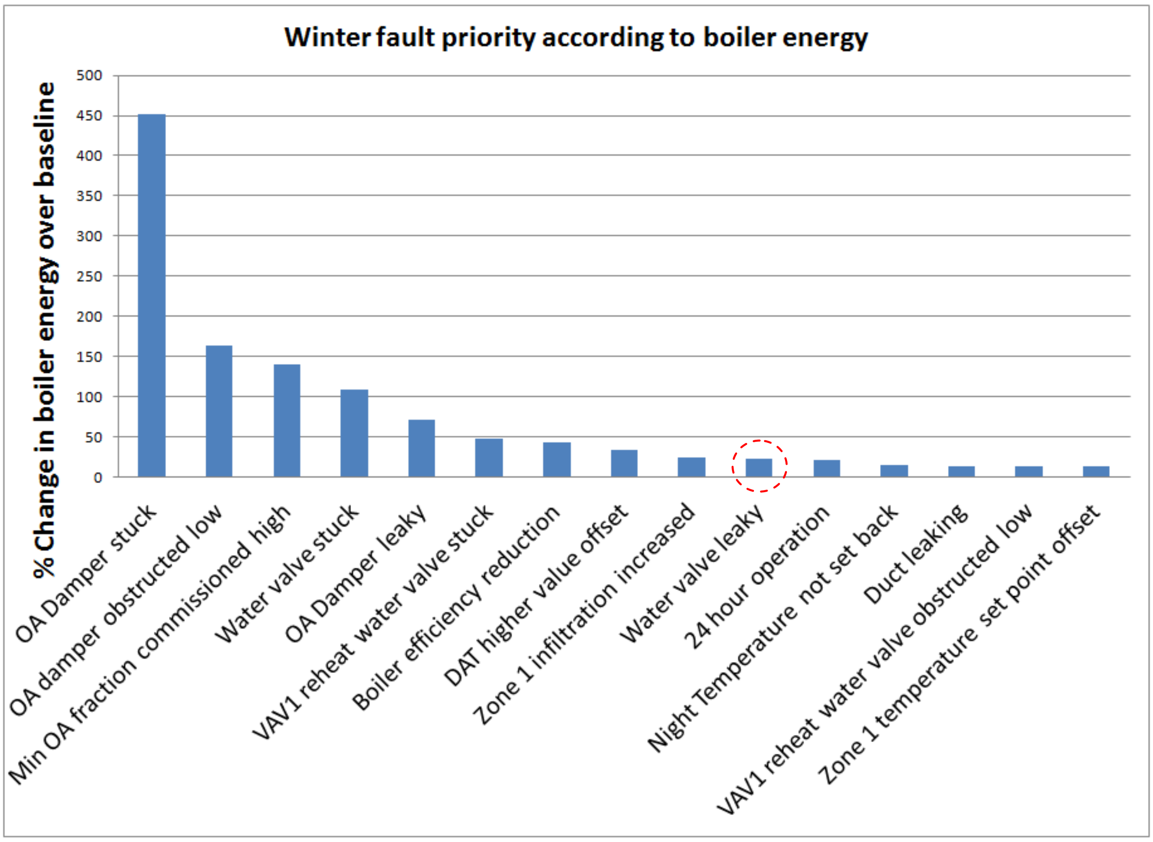

Figure 9: Individual fault prioritization for the winter week based on change in boiler energy (performance measure). Only top-ranked faults are shown.

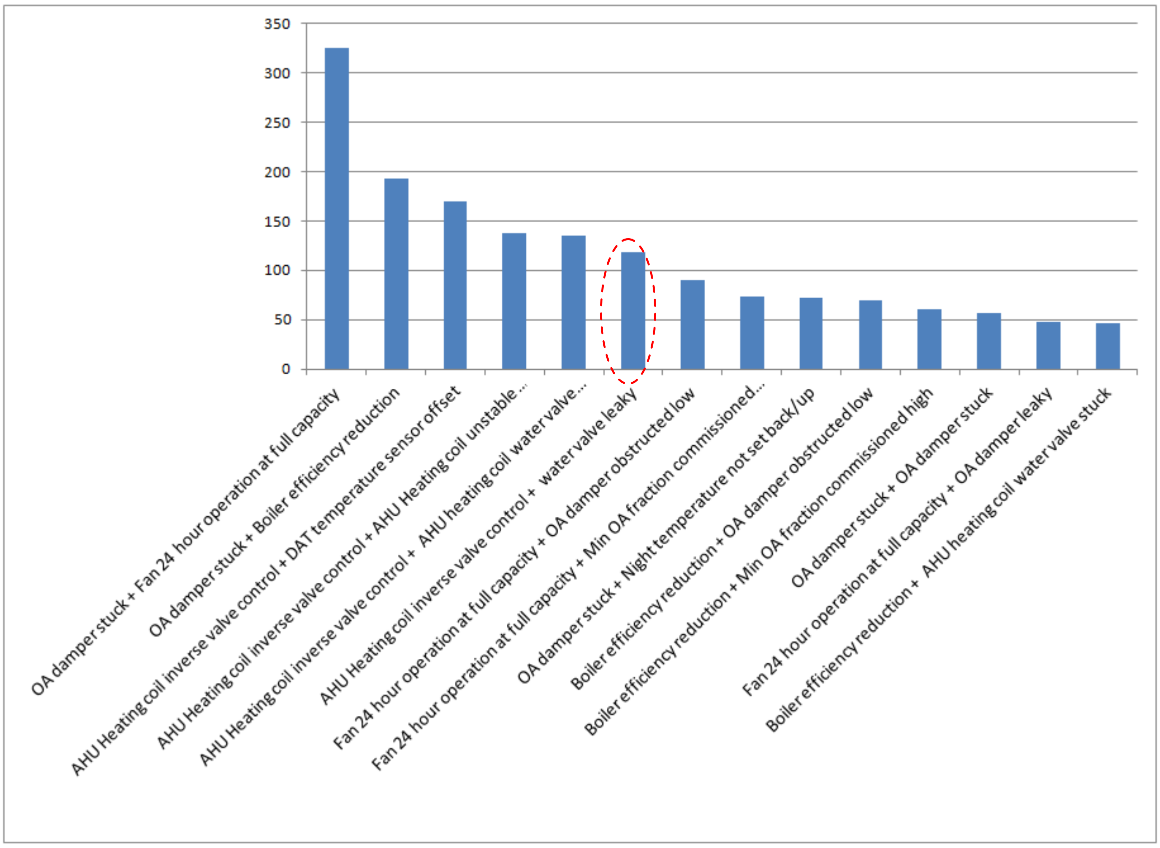

Figure 10: Fault coupling prioritization for the winter week based on change in boiler energy (performance measure). Only top-ranked fault couplings are shown.