PRIORITIZING BUILDING SYSTEM ENERGY FAILURE MODES USING WHOLE BUILDING ENERGY SIMULATION

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ABSTRACT

Building failure modes can be defined as the range of possible faults, mistuning, degradation and wear that can occur in building systems. They drive poor operational energy performance that can be achieved as compared to what was expected in design. If the more critical failure modes can be uncovered early in design, they can be mitigated through design changes or monitoring of associated characteristics on parameters such as temperatures, flow rates and pressures. To understand and prioritize failure modes, failures are characterized through mappings to whole building simulation input variables, and then random sampling methods are applied to simulate the building operating under combinations of different failure modes. Reduced order models are then fit to the resulting data to detemine which failure modes are more critical. The approach is demonstrated on a mid-sized office building, comparing a standard and advanced retrofit design.

INTRODUCTION

Background

In the building retrofit design-build process, it is of benefit to understand not which simulation model inputs are critical, but rather which building failure modes are critical. These are often not the same thing. Design engineers and facility managers think of proper building operation in terms of how component defects or controls errors can cause building systems to operate incorrectly, or *failure modes*. It is proposed that whole building energy simulation models can be used to assess the criticality of failure modes, as outlined here. This is useful to help drive design changes that can mitigate these failure modes, or mimimally help indentify necessary monitoring to prevent energy over consumption.

To do this, defects and errrors that can occur are defined as failure modes and then optimal sampling based methods are applied over the domain of failure modes. At these sample points, energy consumption is calculated through whole building simulation, to then determine criticality of the failure modes through sensitivity analysis. This can then be used, for example, to redesign the systems to create mitigations to the critical failure modes. Further, the results can be used to define requirements for any additionally necessary monitoring and controls.

The approach is demonstrated on a mid-sized office building on the Fort Carson (CO) Department of Defense campus, for both a standard and a low energy building system design. The approach highlighted both expected as well as several unexpected non-linear interactions. Expected critical failure modes included lights being left on or night setbacks not being implemented as designed. Non-obvious ones included the high sensitivity to degradation of circulating flows including chilled or hot water. Process efficiency benefits were also found through having one standard work approach to both parametric uncertainty studies on building simulation inputs (Eisenhower et al 2011b) integrated with the failure mode analysis described here. Both approaches can make simultaneous use of the same whole building simulation sampling set.

Related Work

Lair et al (2000) and Talon et al (2004, 2005) make use of *failure modes and effects analysis* (FMEA) to define failure modes for common building products to provide estimates of reliability and life as used here. Similarly, El-Haram et al (2002, 2003) use FMEA to define high risk failure modes in building systems and from this define cost-effective monitoring and maintenance strategies for a set of buildings, considering expected failure rates on maintenance items. The scope was broad and included all maintenance items from air filters to flooring. The estimated operating cost savings on 18 properties was 18.5%. QSI Inc. (2012) reports on their building systems health management efforts to isolate faults defined through an analysis of

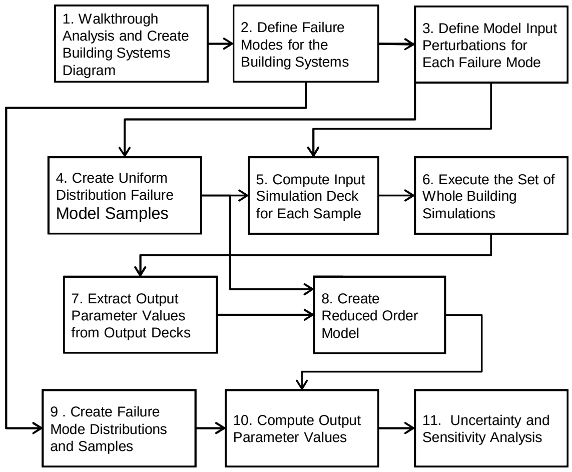

Figure 1: Overall process flow for analyzing effects of failure modes on building energy.

potential failures. Pride (2010) describes how identified building failure modes are used to derive reliability centered maintenance (RCM) programs. The work here is related to these efforts, but focused on energy-related building systems. It is not the objective to identify when systems and components outright fail, but rather to identify when they become misconfigured or out-of-tune and while still apparently fully functional and operating, unnecessarily waste energy.

Others have commented on the need to automate FMEA analysis in buildings, as done here, though for other purposes such as risk management. Touhy (2009) compares the state of BIM and the buildings industry with the state of design automation in the electronics industry. Automated FMEA analysis as proposed here is a desired feature. Heimonen et al (2009) present methods to use FMEA during the design phase to reduce risks during construction, commissioning and operation. There has also been work automating failure mode analysis in other building systems not energy related. Polanco (2012) reports on work to prevent faulty fire alarm through FMEA analysis of the system.

To understand the effects of failure modes, uncertainty analysis and sensitivity analysis (Eisenhower et al, 2011a, 2011b) is used. To do this, the distribution type and parameter values defined affect the sampled behavior of the building model studied. There have been many studies to determine the type of distribution (normal, uniform, log-uniform, etc.) for typical parameters in building models (Dominguez-Munoz et al., 2009, Costola et al., 2010, Clarke et al., 1990, Macdonald, 2002). These works are extended here by presenting a new approach where the uncertainty is estimated based on the FMEA risk *occurrence number* estimate for a failure mode. Low occurrence failure modes (such as with failed valves) have higher tailed, lower occurring distributions compared to higher occurrence failure modes (such as dirty filters) represented with more uniform distributions. Field data can provide estimates for these uncertainties.

APPROACH

To capture the energy loss impact of failure modes in buildings, it is important to capture the effects of not just one failure mode occurring in isolation, but of multiple failure modes occurring simultaneously. Interactions and compounding effects can create situations that cause large energy loss. Rather than exploring these multi-way modes through brute-force enumeration, a process is proposed that makes use of probabilistic methods to explore combinations of failure modes.

The overall process flow is depicted in Figure 1, consisting of 11 basic steps. The first step is a walk-through audit of the existing building, to establish basic building parameters and existing systems configuration. Then alternative retrofit configurations are established, and from this the configurations are analyzed for energy loss failure modes. With the failure modes defined, their effects are mapped to the whole building enerrgy simulation input variables. The failure modes are then sampled for combinations to simultaneously simulate, using optimal sampling based methods. With these failure mode samples, a set of whole building energy simulation input decks is computed, each slightly different in input variable values, according to the failure modes of each sample. These decks are executed to compute a set of whole building simulation output decks. The relevant output parameter values of interest are extracted from these decks, namely the energy consumption and hourly peak power demand loads. Then an uncertainty analysis and sensitivity analysis is completed, relating the sensitivity back to the input failure modes.

The first step is to define the systems in the building to analyze for energy loss failure modes. This includes establishing basic building parameters such as layout, floor plans, zones, schedules, and material construction. It also includes the different equipment selections for different scenarios to analyze.

The first result of this work for modeling purposes is a set of block diagrams depicting the building systems, the set of which describes graphically all energy related systems in the building. Constructing a block diagram is an exercise of diagramming all energy related components in the building and their interconnections. Generally this is a connected set of functional components and their interactions at end points of occupancy zones. The second result of this step is a complete whole building energy simulation, generally an EnergyPlus or TRNSYS model.

With the building systems depicted graphically for interrogation and with a complete whole building energy simulation model, Step 2 is to define the failiure modes of the building. Examining the flows of energy through the system block diagrams, possible modes of unintended loss can be considered. For example, the air flow can be studied from outdoor air entry into the ductwork through delivery to individual zones. Each component can be considered in turn for how it can fail, and how that can impact parameters of the system. The OA damper for economizer can fail fully closed, partially closed, partially open, fully open, or can be commanded incorrectly to any of these conditions.

To systematically address all failure modes in the building, standard work procedures are used to define the failure modes (DOD, 1980). Using a traditional FMEA, one scrutinizes the functional block diagram of the system, and then creates a list of how the system blocks and interconnections can fail. To each of these failure modes, the severity of the failure is assessed as an individual rating. Further, the likelihood of occurrence is also assessed as a probability, perhaps subjectively. Lastly, the ability to detect that the failure mode has occurred before the severity impact has occurred is also assessed as a separate detectability score. The product of the severity, occurrence and detectability scores define each failure mode's risk quantitatively as a risk priority number. Sorting this list provides the top most critical failure modes. One then defines mitigation plans for each risk, to reduce the risk level. All such failure modes are listed in a standard FMEA worksheet.

The result of the traditional FMEA analysis is a list of failure modes, and an estimate of their likelihood of occurrence. For this approach, an estimate of severity is unecessary (as commonly estimated in a traditional FMEA analysis) since the analytic modeling provides the severity assessment in terms of energy loss associated with the failure mode. Similarly, the detectability rating common to an FMEA is also not necessary here, since the objective is to design the building monitoring and controls to be robust against the high severity commonly occurring failure modes.

The next Step 3 is to map each failure mode to an associated set of inputs to the whole building energy simulation model. It is often not a simple mapping of considering each input individually, the mapping can be anything from many-to-one to one-to-many. For example, a typical building energy model variable is the leakage rate in a zone, often expressed as a percent of the air exchange rate. Failure modes of duct leakage or open windows, for example, could both contribute to variations in the simulation variable of leakage rate. On the other hand, a controls system failure mode of the building lights being incorrectly forced on and left on 24-7 can affect the zone lighting schedule variables, one variable for each zone. In this way, one can create a mapping from each failure mode the set of inputs in the associated building energy simulation model.

The next step is to quantify the mapping between each failure mode and the range of perturbation on each associated simulation variable. This is done by introducing a *participation level* for any failure mode as a zero to one variable. When a failure mode is not active, its participation level is zero. When a failure mode is fully active, its participation level is one. Intermediate levels of failure mode participation are defined as a value between zero and one.

Mathematically, the failure modes must be mapped to the building energy simulation input variables. Practically, there are three types of failure mode mappings to simulation input variables: *unilateral*, *bilateral*, and *discrete*, when considering a building energy simulation input variable and its associated mapped failure mode probability distribution.

The unilateral map is easiest to consider, the upper and lower range of a building energy simulation input variable is defined for the zero and full participation levels of the failure mode. For example, an economizer failure mode can prevent complete closure, and so is mapped to the economizer air flow rate from zero to 5% of the nominal full flow level.

The bilateral map is slightly more complex, since a zero value of the failure mode participation means the building energy simulation input variable is at nominal, and then as the failure mode increases in participation to one, the building simulation input variable value increases or decreases to the max or min. For example, consider the failure mode of an economizer improperly commissioned slightly high or low from the desired outdoor air flow rate. This can be mapped to plus or minus 2% of the nominal outdoor air refresh rate.

Finally, the discrete mapping is the nominal discrete value at zero failure mode participation, and then can take on any of the other values according to a discrete map from the failure mode participation variable. Generally this map is constructed by providing each discrete value an associate range of participation such that it has the desired level of probability of occurring. For example, an economizer control failure mode may incorrectly command the economizer to be open when it should be closed. This can be mapped to "on" or "off" over-ride to the economizer set point variable, each with a probability of occurrence.

Having defined each failure mode's mapping to the building energy simulation inputs, one can turn each failure mode "on" one at a time, and compare the results with no failure modes active. This would provide an indication of the impact of a failure mode occurring in isolation, with all other failure modes not active and their related building systems operating perfectly at design intent. This approach ignores interactions. For example, an economizer and a chilled water supply valve both stuck partially open will cause much more energy loss than either failing alone or compared to their linear addition.

To explore this, first multiple failure modes that can impact the same simulation input variable must be resolved. For example, there are several failure modes associated with the single building energy simulation input representing the fraction of outside air. Therefore one must define how multiple failure modes interact, and any precedence relations. Many failure modes simply add, particularly the unilateral and bilateral failure modes. A restricted outdoor air economizer and an economizer setpoint error failure mode simply add in their impact on the economizer flowrate simulation input variable. However, an outdoor air economizer controls error such as setting the valve fully closed when it should be open is a failure mode that does not add with the previous; rather, it over-rides the setpoint value to zero. This logic amongst the failure modes to building energy simulation input variables must be constructed.

The next Step 4 is to sample the failure mode participation level space, an n-dimensional [0,1] compact space, to represent the domain with a finite sample set. Ultimately, the sampling is done according to the probability distributions defined on the failure mode participation levels discussed earlier. That is, some failure modes have very low occurrence rates, reducing their risk levels in actual practice, compared to their sensitivity. If a failure rate only occurs once every ten years, it is perhaps of less concern than one that occurs monthly, if they have the same energy impact. To have a distribution sampling rate sufficient to capture very rare events, however, requires very high sampling rates, particularly to ascertain compounding interactions with other failure modes.

Therefore, a two-step approach is applied to sampling, as shown in Figure 1. First, the occurrence rates from the FMEA are ignored, and all failure modes are sampled uniformly. The energy results are computed using the whole building simulation at each sample point, which is computationally intensive. This approach clarifies each failure mode's contribution to energy consumption and how they interact with other failure modes. The results are fit to a reduced order model, to easily and quickly indicate how all failure modes individual and together affect energy consumption.

Then separately the actual risk is computed, incorporating the FMEA occurance rates of the failure modes. To do this, the failure modes are sampled a second time, but this time using their actual occurrence rates. The expected energy consumption levels from the failure modes given their occurance rates are thereby computed. This can be done even for rare failure modes by using very large sampling rates, since the reduced order model computes much more quickly. To do the sampling, advanced optimal spaced sampling techniques are applied (Eisenhower 2011b). This provides a minimal sample set that can cover the failure mode participation distributions. The result is a matrix of samples, where each failure mode is a column and each sample is row. Each sample has a [0,1] value for each failure mode, representing the participation level of each failure mode in the scenario represented by the row sample.

The next Step 5 is to map the matrix of failure mode participation level samples to building energy simulation inputs. Practically, this means creating a slightly varied building simulation input deck for each row of the failure mode participation sample matrix. For each row in the matrix, a separate building simulation input deck is created and populated. Step 6 is then to execute the set of input decks on a high performance computing cluster, to quickly compute each simulation. This computation is intense, but can be highly parallelized. The result is a set of building energy simulation output decks, each slightly different in values according to the varied performance impacts of the different participation levels of the failure modes occurring simultaneously.

Once all sample runs are complete, as Step 7 the set of output decks is parsed and the desired energy and power figures are extracted. Typically, this involves summing the energy data over the 8760 hours of simulated building operation over a simulated year, as well as recording the peak hourly consumption figures. The result is an output matrix with columns of the output energy and peak power metrics, and number of rows as the number of samples.

With this matrix of input and output samples, in Step 8 a rapid simplified model is determined, making use of reduced order model surface fitting techniques. The result is equations that represent how each failure

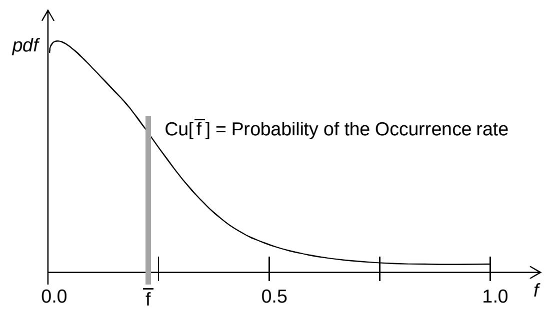

Figure 2: Failure Mode Participation Probability Density Function.

impacts energy consumption, and further how each interacts with others to impact energy consumption together. These equations are independent of the actual occurrence levels and associated probability distributions of the failure modes. The next step is to modulate the risk levels of each failure mode energy sensitivity according to how likely each is.

Most failure modes are not active at any given moment, or only slightly active. For example, a duct can be blocked and cause a high pressure loss as a failure mode. More likely is the duct work is only slightly degraded, and so the failure mode is only partially participating and contributes a slight pressure loss. This character is captured using a failure mode participation probability function, where over the [0,1] domain of the failure mode, a probability distribution is defined. A distribution biased toward zero participation is used, according to the expected probability of occurrence associated with the occurrence rate defined in the FMEA.

From the expected probability of occurrence, a participation level probability distribution is defined such as shown in Figure 2. The function is defined by the observation that the cumulative probability out to the expected value of a failure mode's participation distribution should equal the probability of the occurrence rate. This rule constrains the probability distribution, which with a desired shape definition such as a long tail, exponential, or Weibull distribution, provides sufficient information to define the failure mode distribution function. These distributions are defined on each failure mode according to the FMEA occurrence rates, and then the distributions are sampled, similar to Step 4, but not using uniform distributions. With the actual distributions, some of which can be highly skewed, the sampling must occur at much higher rates.

Using the very rapid reduced order model, in Step 10 the output energy consumption levels are computed for each sample point of failure mode participation levels. This is a very rapid calculation set over many sample points, as compared to Step 4. The next Step 11 is to analyze the output matrix data as sampled values of distributions, for each output metric. The shape of the distribution is of interest, to determine any bias from nominal operating conditions, large outliers, etc. Finally, the inputs failure mode participation levels are correlated with output energy consumption and peak power metrics. Through correlation, regression, and variance decomposition techniques, the failure modes that drive excess energy and peak power consumption above the as-designed condition can be determined.

Table 1: Existing Design Energy Intensity for Building 1225 (kBTU/ft^2/yr)

HEATING	COOLING	PUMPS	FANS
20.5	3.2	1.3	13.6
LIGHTING	PLUG	TOTAL-PLUG	TOTAL
12.7	29.5	51.4	80.9

An issue is the simulation model error compared to actual building performance. Generally, a model is needed that can relatively prioritize failure mode effects. Whole building simulation provides this level of accuracy, with exceptions of failure modes that extend beyond the assumptions of the whole building simulation. For example, failure modes that amplify inter-zonal air mixing are beyond the capability of whole building simulation and so cannot be prioritized in this approach without extension to incorporating such models.

DEMONSTRATION: FORT CARSON BUILDING 1225

To demonstrate the methodology, consider a mid-sized office building on the Fort Carson (CO) DoD campus. The single floor building has two separate wings, 22,300 square feet total with 18,631 square feet occupied, two separate constant volume air handling units, and 18 separate zones. The building was scheduled for energy reducing retrofits, and was analyzed in the existing configuration and the proposed retrofit configuration. The intial pre-retofit condition is termed the *existing design* configuration, and the proposed retrofit condition is termed the *advanced design* configuration.

In the existing design condition, the Energy Use Intensity is 80.9 kBTU/ft^2, putting it at a rating of 24 in the EnergyStar Portfolio Manager database, or that it is in the bottom 24% of buildings in its class of usage and climate. The building was also instrumented and

Table 2: Distribution of Failure Modes.

	ALARMED	MODELED	OUTSIDE MODEL	TOTAL
Envelope	0	26	10	36
HVAC Equip.	10	42	12	64
HVAC Controls	29	173	192	394
Internal Gains	0	1	2	3
Int. Gain Controls	0	35	`1	36
Total	39	277	215	533

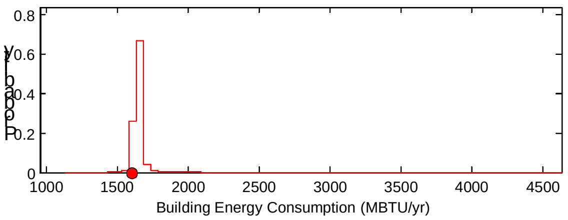

Figure 3: Distribution of Overall Building Energy Consumption over the Failure Modes.

measured over a limited duration. Based on this, the building was measured with an Energy Use Intensity at 101 kBTU/ft^2 as operated in a 24-7 capacity (13% difference). Accounting for the differences in operating schedule at the time of measurement, the energy use is comparable.

The breakout of the energy consumption is shown in Table 1. The vast majority is going into plug loads, followed by heating, air circulation and lighting.

These results suggest failure modes that cause energy performance degradation can be understood, quantified, and simulated. For this existing configuration, the next step is to consider not only the observed failure modes in the particular state of maintenance and equipment replacement at the time, but all possible failure modes at any future state, to determine what failure modes are most critical to manage.

Building 1225: Existing Configuration – Critical Failure Modes

The existing design's existing systems were depicted as a set of block diagrams representing all energy related systems and interconnections in the building. This was then analyzed for all failure modes of all components and their interconnections. There were 38 systems and zones with 89 critical components to analyze, and 533

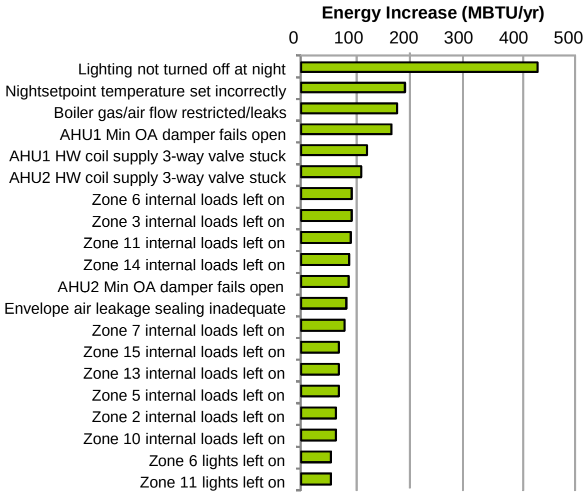

Figure 4: Sensitivity of Overall Building Energy Consumption to the top contributing Failure Modes.

failure modes in the building energy systems (lighting, hvac, power, controls, etc.).

The distribution of failure modes are shown in Table 2. There are three columns, indicating the need or ability to model the failure mode. The rows indicate general categories of building systems. The "Alarmed" column indicates failure modes that, should they occur, will generate an immediate response from occupant complaints. For example, if the boiler fails, there will be no heat, occupants will complain and the failure will be addressed. These failure modes are not necessary to model here, where the focus is on energy loss failure modes that do not necessarily cause a sufficient comfort complaint. Such energy loss failure modes are represented in the "Modeled" column of Table 2. These are failure modes such as missing insulation, stuck economizers, etc. Finally, there are failure modes that can exist in the building, but cannot be directly modeled in whole building simulation tools, and so are estimated outside the model. These are typically pressurized flow of air between zones, control system feedback dynamics, or other short cycle dynamics.

Given these failure modes, an ensemble of simulations were performed, and the variability in building systems performance assessed due to failure modes. The modeled impact of failure modes on the energy consumption for the system is substantial, with the deviations operating at 15% higher energy consumption rate than when all systems operating perfectly at the nominal as-designed conditions. The distribution of total energy consumption is shown in Figure 3, indicating the spread of energy consumption across the failure modes.

Table 3 Existing Design Energy Intensity for Building 1225 (kWhr/m²/yr)

HEATING	COOLING	PUMPS	FANS
11.9	1.8	0.3	5.8
-38%	-41%	-79%	-50%

LIGHTING	PLUG	TOTAL-PLUG	TOTAL
8.5	29.5	28.3	57.8
-33%	0%	-41%	-26%

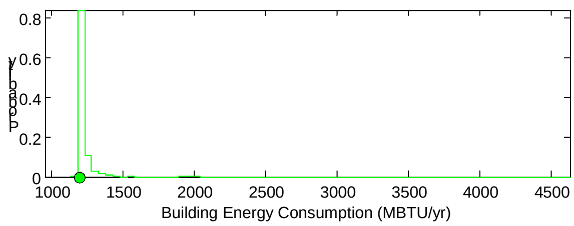

Figure 5: Distribution of Overall Building Energy Consumption over the Failure Modes.

Note the overall accuracy of the simulation compared to measured data was 13% with no attempt to precisely align schedule, weather patterns or possible failure modes active during the building energy measurement period. Therefore, the results shown in Figure 3 are comparable to the actual observed deviation from perfect operation. Further, an absolution prediction of energy consumption is not required, the real objective is to relatively prioritize the failure modes.

Given the distribution of energy consumption from all of the various failure modes, some contribute more than others. The primary largest contributing failure mode causes were identified as outlined in Figure 4, as determined by the sensitivity analysis described in Figure 1. The largest contributing failure modes to overall energy consumption included the lights being left on all night and the night temperature setback not being used. Assuming these occur and happen every day, these double the energy consumption. On the other hand, such occurrence rates are not expected, and so the energy distribution is smaller (Figure 3).

Overall, the standard, traditional existing system configuration of building 1225 shows a design intent of 80.9 kBTU/ft^2 energy intensity. When considering failure modes and their expected occurrence rates with reasonable maintenance, this increases by 15%. If any of several failure modes occur continuously throughout the year, the energy increase can be much more substantial and easily double the energy consumption of the building. Given these results, next a low energy design retrofit concept was explored for Building 1225, discussed next.

Building 1225: Advanced Design – Critical Failure Modes

The systems in Building 1225 were also explored as high efficiency retrofits. The HVAC system was explored as a high efficiency solar thermal system retrofit with the campus steam as backup. The cooling system was explored with an evaporative cooling system retrofit with the campus chilled water system as backup. The constant air volume systems were retrofitted with VAV distribution for higher efficiency. High efficiency fluorescent lighting was considered. No advanced occupancy based controls were considered, given the building has a high 24-7 occupancy. Also, the only envelope measures considered were double pane windows. Nonetheless, this retrofit solution upgrades Building 1225 to a design intent of 58 kBTU/ft^2, a 28% overall reduction with rather modest interventions and places the building at an EnergyStar Portfolio Manager rating of 54, a 100% improvement. The low rating is entirely due to the unusually high internal computing loads and unusually high 24-7 occupancy rate and schedule.

The breakout of the energy consumption is shown in Table 3. The majority is going into plug loads, followed by heating, air circulation and lighting. Similar to the existing building systems configuration, the advanced systems in the building were diagrammed into a set of block diagrams representing all energy related systems and interconnections in the building. This was then analyzed for all failure modes of all components and their interconnections. There were 43 systems and zones with 98 critical components to analyze, and 565 failure modes in the building energy systems (lighting, hvac, power, controls, etc.).

The results on the advanced system design show substantial impact of failure modes on the energy consumption, with the expected average operation at 20% higher energy consumption rate than the operation with all systems operating perfectly at the nominal as-designed conditions. The distribution of total energy consumption is shown in Figure 5, indicating the spread of energy consumption across the failure modes. The range of uncertainty is slightly larger than the existing building configuration. Also, with the decrease in nominal energy consumption, the percent uncertainty is larger. Energy efficient buildings tend to be more sensitive to variability from failure modes.

Given the distribution of energy consumption from all of the various failure modes, some contribute more than others. The primary largest contributing failure mode causes were identified as outlined in Figure 6. The largest contributing failure modes to overall energy consumption included the lights not turned off at night, and the night temperature setback not operating. These failures are shared with the nominal existing system design, though in different order of sensitivity.

Overall, the advanced retrofit design configuration of building 1225 shows a design intent of 57.8 kBTU/ft^2 energy intensity. When considering failure modes, this increases by an expected 20%. If any of several failure modes occur continuously throughout the year, the energy increase can be much more substantial and easily double the energy consumption of the building.

CONCLUSION

A methodology for system model-based FMEA for high performance building design assessment is developed and evaluated for an existing building use case. Typical equipement failure modes are shown to increase energy consumption by 20% when taken together, which is comparable to observed overconsumption of actual buildings versus their design intent. Analysis of building energy over-consumption due to system failure modes is feasible using whole building energy simulations with parametric sensitivity analysis tools. Failure modes are defined, related to the whole building energy simulation inputs, and then sample-based methods are used to evaluate energy performance for each sample of failure mode combinations. Performing a sensitivity analysis on the results can indicate which failure modes are more significant in contributing to energy consumption.

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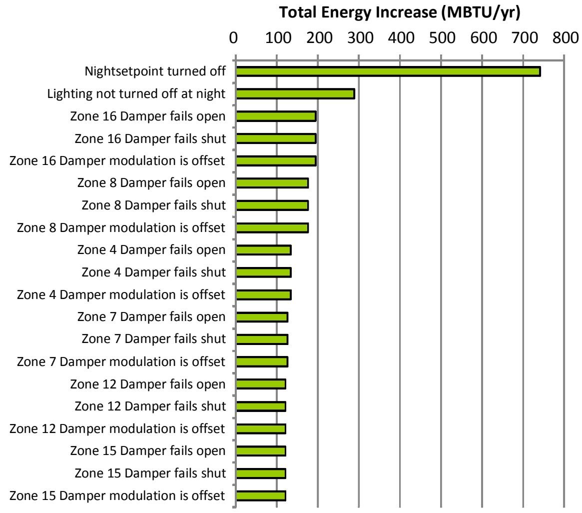

Figure 6: Sensitivity of Overall Building Energy Consumption to the top contributing Failure Modes.

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