ESL-IC-12-10-02a

Two Similarity Measure Approaches to Whole Building Fault Diagnosis

12th International Conference for Enhanced Building Operations
23rd - 26th October 2012
Manchester, England

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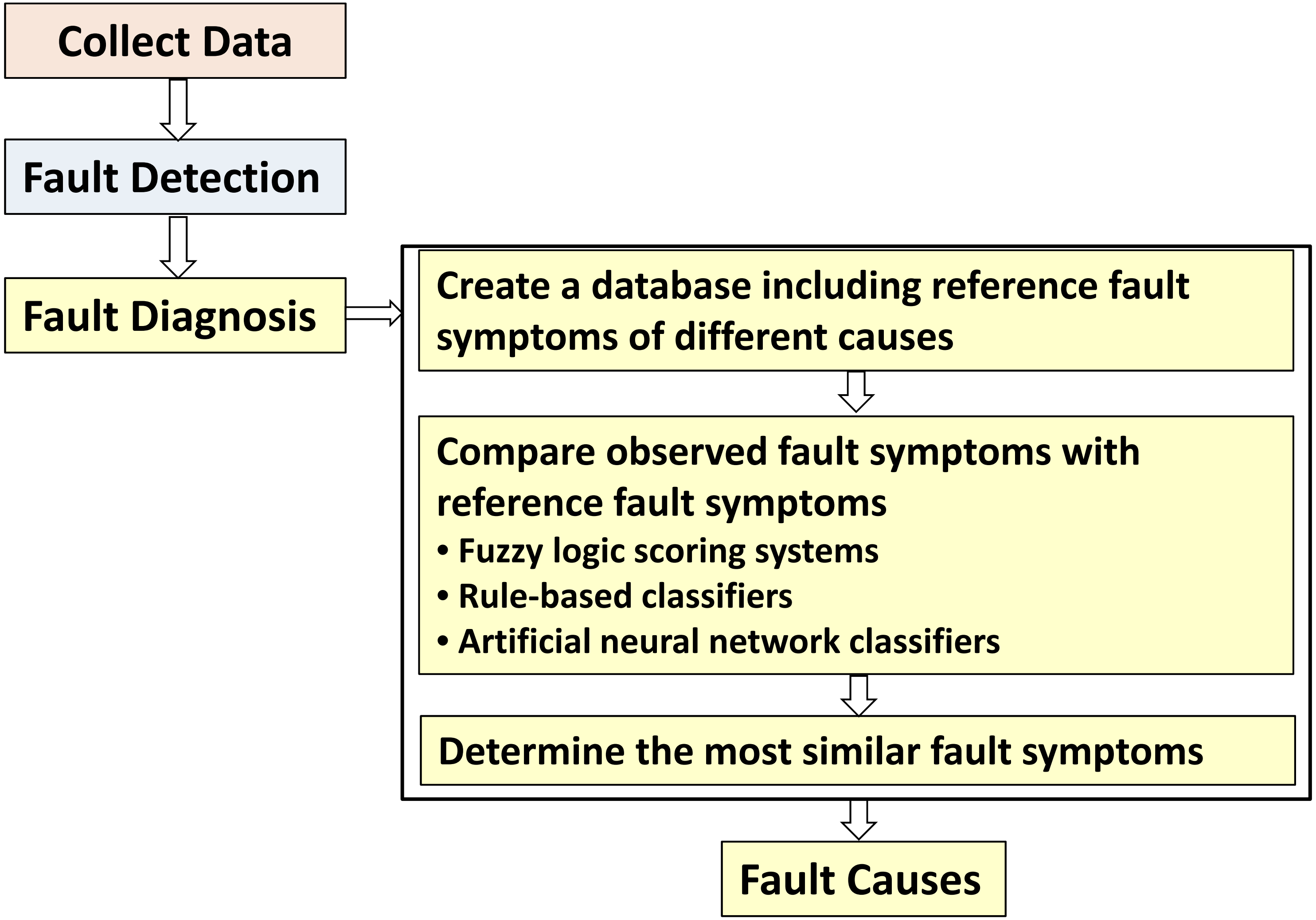
Introduction

- Whole building fault diagnosis
  - A process of identifying possible causes of detected abnormal energy consumption faults
  - Based on energy consumption and weather data
- Most of the previous whole building fault detection and diagnosis research focused on fault detection
- A general scheme to diagnose fault at whole building level is seldom mentioned

Typical HVAC FDD Process

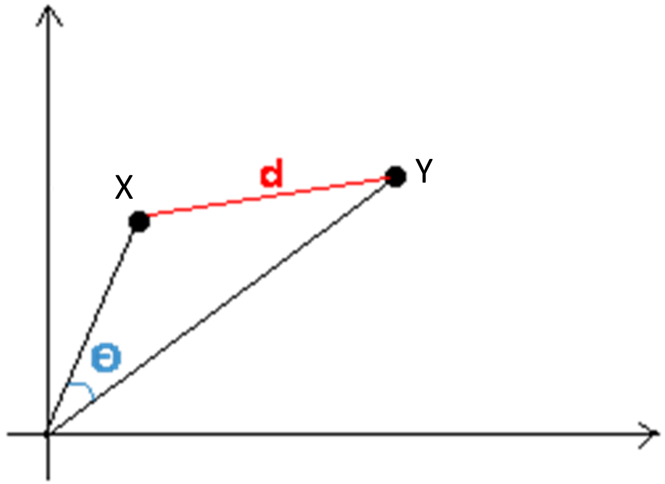


(Rossi and Braun 1997, Friedman and Piette 2001)

Similarity Measures

- Widely used in pattern recognition
- Quantitatively represent the degree of compliance within vectors
- Cosine similarity
  - Direction-based measure
  - Range: [-1,1]
    - 1 - exactly the same
    - 0 - Independence
    - -1 - exactly opposite

$$S_c(X,Y) = \cos(X,Y) = \frac{\sum_{i=1}^{n} X_i Y_i}{\sqrt{\sum_{i=1}^{n} X_i^2}\sqrt{\sum_{i=1}^{n} Y_i^2}}$$



- Euclidean distance similarity
  - Distance-based measure
  - Range:(0,1]
    - 1 - exactly the same

$$S_d(X,Y) = e^{-d(X,Y)}$$

$$d(X,Y) = \sqrt{\sum_{i=1}^{n} (X_i - Y_i)^2}$$

(Candan and Sapino 2010)

Application of Similarity Measures

- Application in fault diagnosis
  - Fault isolation in the chemical industry(Yoon and MacGregor, 2001)
  - Oil-immersed transformer fault diagnosis(Li and Dai, 2005)
  - Fault diagnosis of a turbine(Lee et al. 2009)
  - Fault diagnosis in an automotive infotainment application (Kabir, 2009)
- Application in HVAC
  - Use Euclidean distance similarity for determining days with similar energy consumption profiles (Seem, 2004)
  - Use cosine similarity to locate historical data having similar operating conditions as the investigated data (Li, 2009)

New Whole Building Fault Diagnosis Methods

- Target
  - Limit the possible fault causes to several options
  - Rank the options according to their probability
- Similarity methods
  - Cosine similarity
  - Euclidean distance similarity

Calibrated Simulation Model

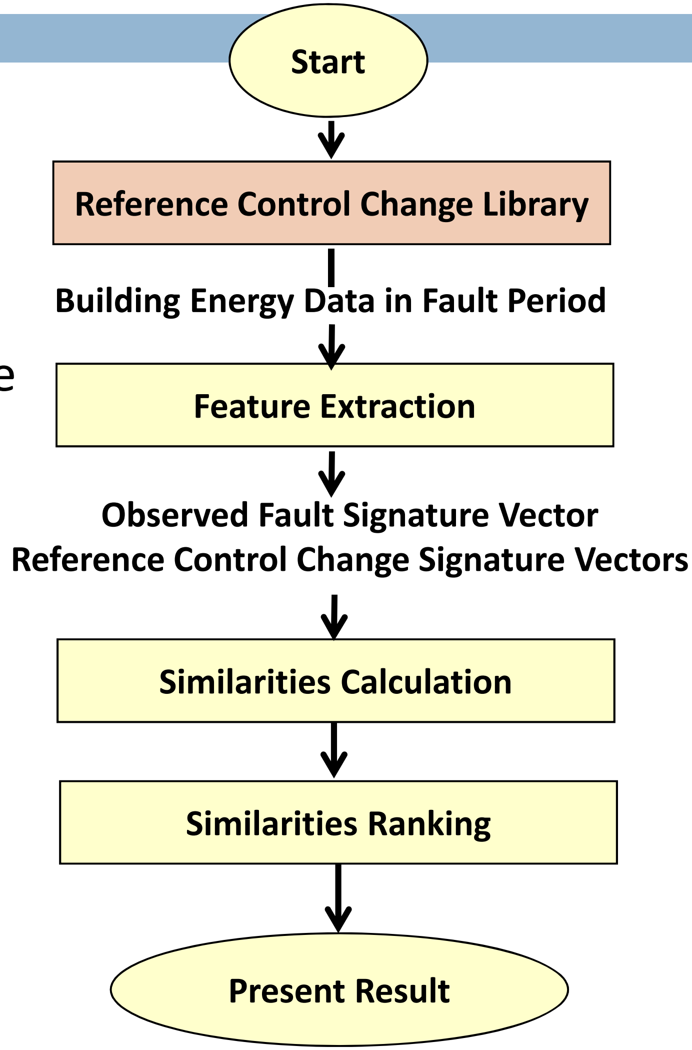
- Use calibrated simulation model in ABCAT (Curtin 2007)to predict energy consumption
  - Normal energy consumption
  - Energy consumption under different operational changes
- Inputs
  - Building and HVAC system info
  - Weather
- Baseline period
  - From a post-commissioning period
  - No faults
  - Cover wide range of Toa and RH fluctuation

ABCAT: Automated Building Commissioning Analysis Tool

Methodology

- Step 1: Reference control change library determination
  - Whole building level control changes
  - Multiple levels of severity for a control change

Reference Control Change	Magnitude I	II	III	IV	V	Units
X_{oa} decrease	-10%	-20%				
X_{oa} increase	10%	20%	30%	40%	50%	
T_{prec} decrease	-2	-4	-6	-8	-10	°F
T_{prec} increase	2	4	6	8	10	°F
T_{cl} decrease	-2	-4	-6	-8	-10	°F
T_{cl} increase	2	4	6	8	10	°F
X_{max} decrease	-10%	-20%	-30%	-40%	-50%	
X_{max} increase	10%	20%	30%	40%	50%	
T_{rc} decrease	-2	-4	-6	-8	-10	°F
T_{rc} increase	2	4	6	8	10	°F
T_{rh} decrease	-2	-4	-6	-8	-10	°F
T_{rh} increase	2	4	6	8	10	°F



Methodology

- Step 2: Feature extraction
  - Generate observed fault symptom and reference fault symptoms in fault period using calibrated simulation model

$$V = [fs_{CHW}, fs_{HW}]$$

  - Observed fault vector

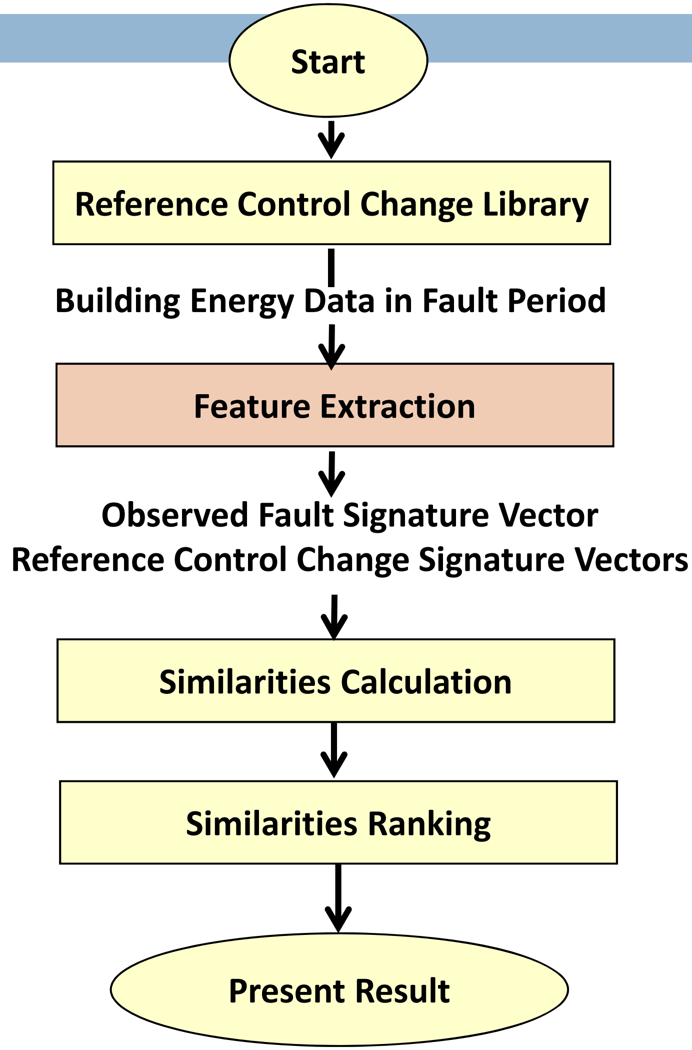
$$fs_{CHW} = \frac{CHW_{mea} - CHW_{sim\_faultfree}}{E_{AveBaseline}}$$

$$fs_{HW} = \frac{HW_{mea} - HW_{sim\_faultfree}}{E_{AveBaseline}}$$

  - Reference control change signature vectors

$$fs_{CHW} = \frac{CHW_{sim\_refc} - CHW_{sim\_faultfree}}{E_{AveBaseline}}$$

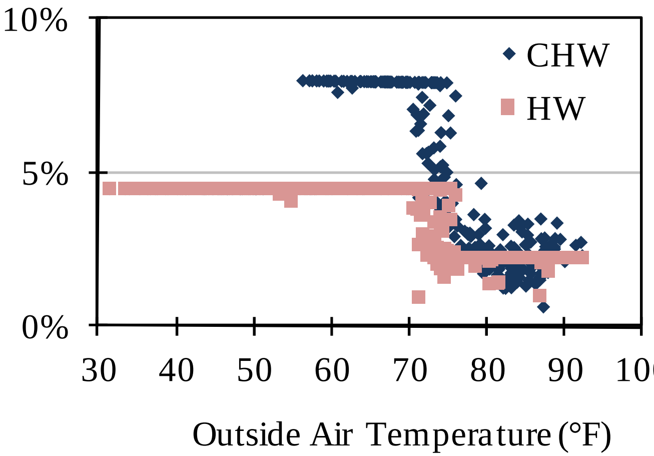
$$fs_{HW} = \frac{HW_{sim\_refc} - HW_{sim\_faultfree}}{E_{AveBaseline}}$$

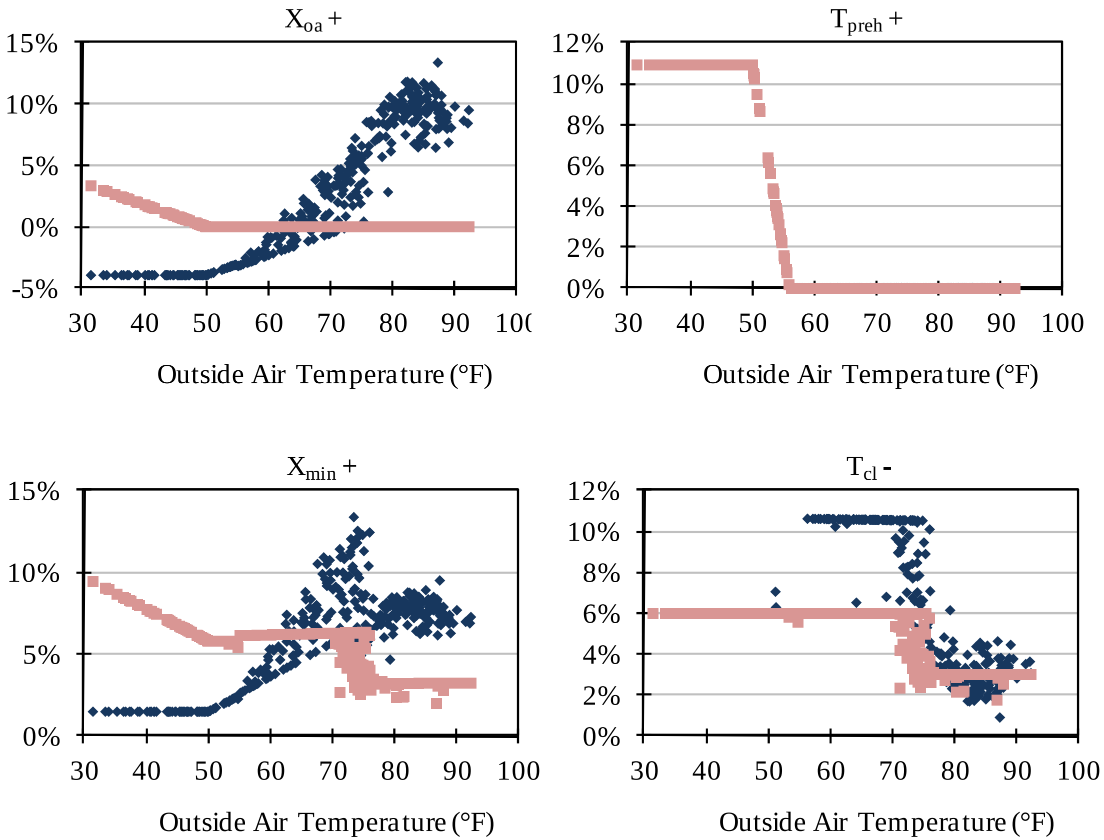


$E_{AveBaseline}$: Daily average cooling plus heating energy consumption in the baseline period

Reference control change signature vectors

Observed fault vector

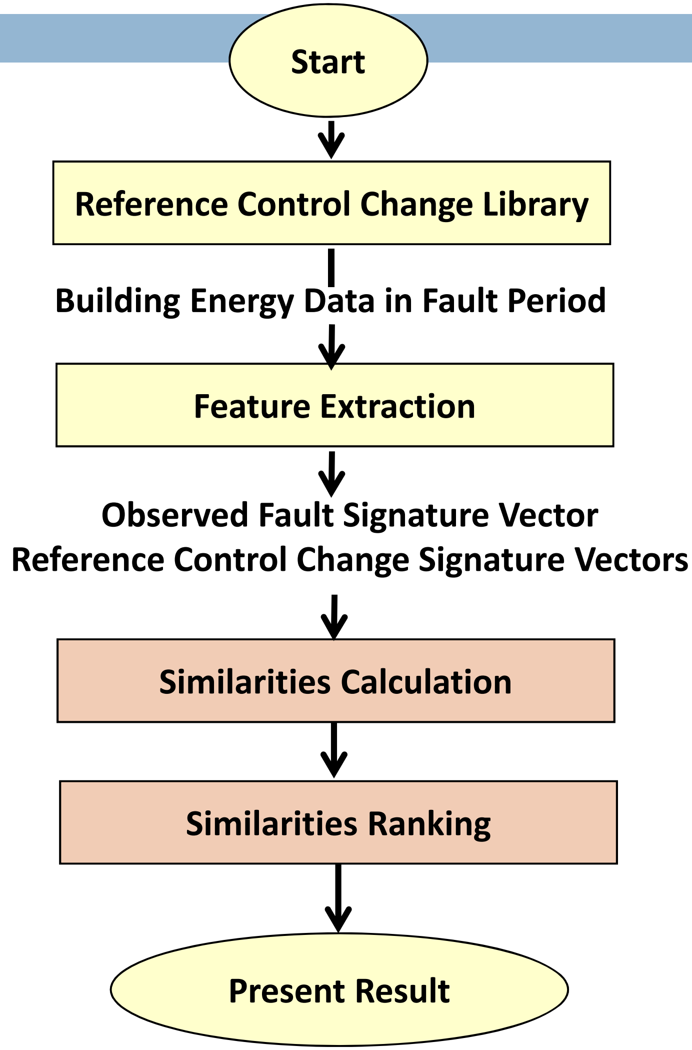




Methodology

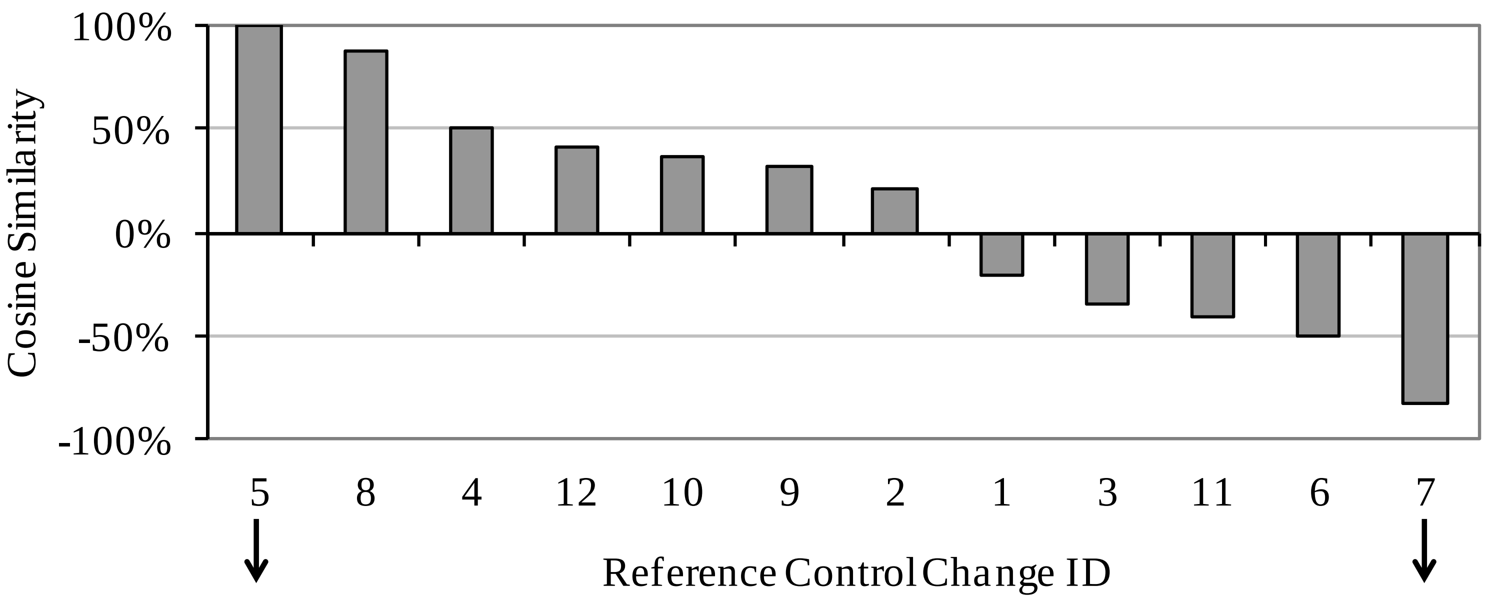
- Step 3: Similarities calculation
  - Calculate the similarities between $V_{observe}$ and each of the $V_{ref\ c}$
  - Choose representative similarity of each reference control change
- Step 4: Similarities ranking
  - Sort reference control changes by representative similarities in descending order
  - **Larger similarity value**

    = Higher probability



Cosine Similarities Ranking

- Diagnostic result: T_{cl} decrease



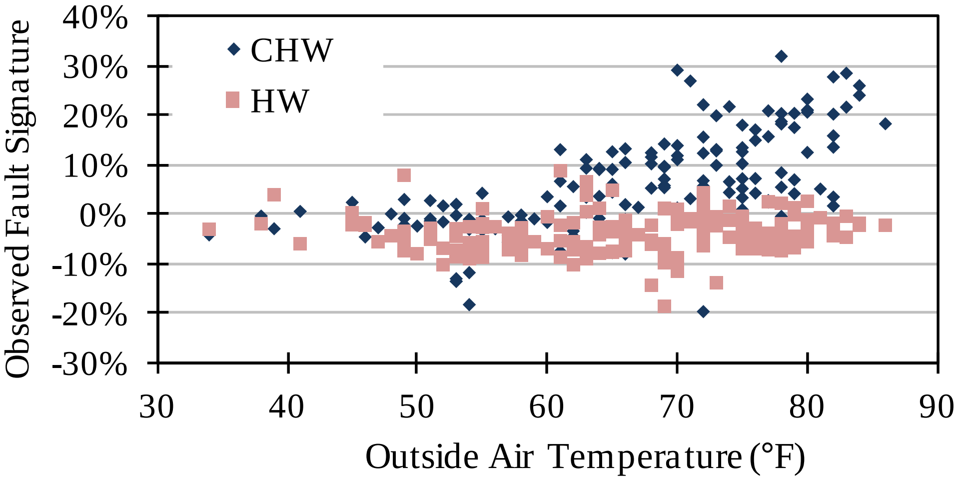
T_{cl} decrease
Most likely cause

X_{max} decrease
Most unlikely cause

T_{cl}: Cooling coil discharge temperature
X_{max}: Maximum designed airflow volume

Field Test Building

- Sbisa Dining Hall
  - SDCV system
  - Fault period:1/1-6/4/2006
  - Exceptionally low precooling outside air temperature

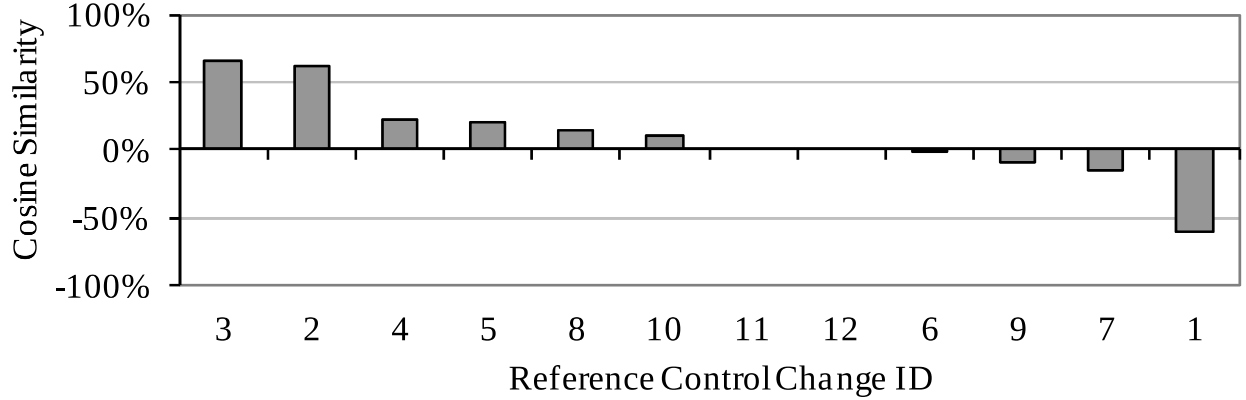


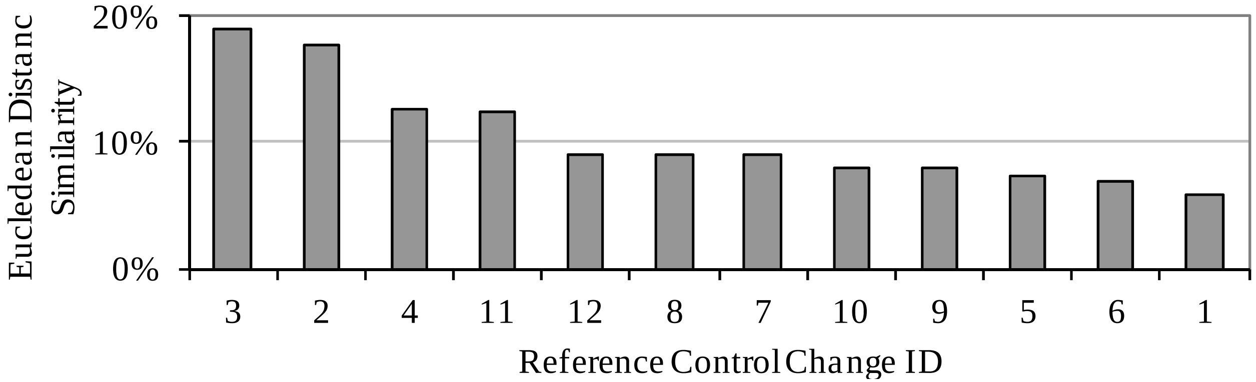
Reference Control Change Library

ID	Reference Control Change	Magnitude					Units
		I	II	III	IV	V	
1	Outside airflow ratio (X_{oa}) decrease	-10%	-20%				
2	Outside airflow ratio increase	10%	20%	30%	40%	50%	
3	Outside air precool temperature (T_{prec}) decrease	-2	-4	-6	-8	-10	°F
4	Outside air precool temperature increase	2	4	6	8	10	°F
5	Cooling coil leaving temperature (T_{cl}) decrease	-2	-4	-6	-8	-10	°F
6	Cooling coil leaving temperature increase	2	4	6	8	10	°F
7	Maximum airflow ratio (X_{max}) decrease	-10%	-20%	-30%	-40%	-50%	
8	Maximum airflow ratio increase	10%	20%	30%	40%	50%	
9	Room cooling set-point temperature (T_{rc}) decrease	-2	-4	-6	-8	-10	°F
10	Room cooling set-point temperature increase	2	4	6	8	10	°F
11	Room heating set-point temperature (T_{rh}) decrease	-2	-4	-6	-8	-10	°F
12	Room heating set-point temperature increase	2	4	6	8	10	°F

Diagnosis Results

- A decrease in precooling outside air temperature

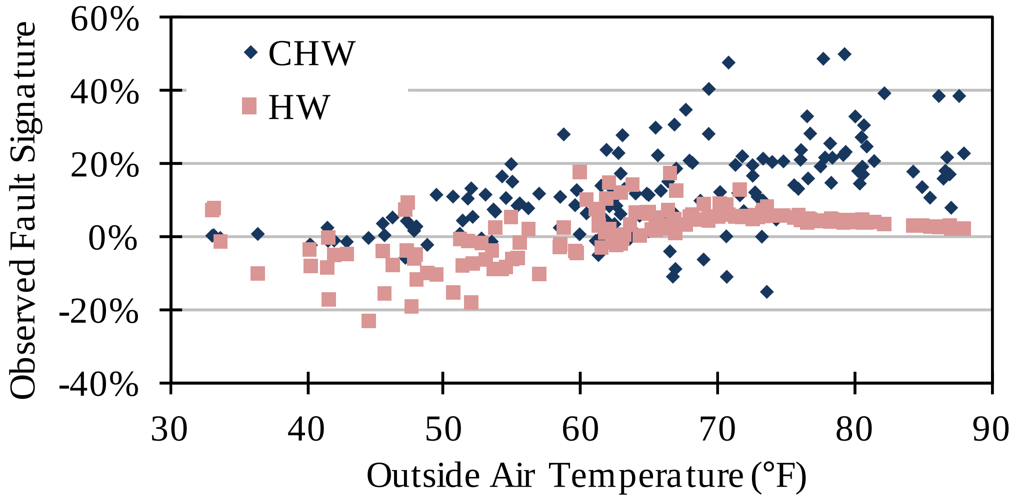




3: Precooling outside air temperature decreases
2: Outside airflow ratio increases

Field Test Building

- Bush Academic Building
  - DDVAV system
  - Fault period:11/1/2008-6/30/2009
  - A preheat valve leaking

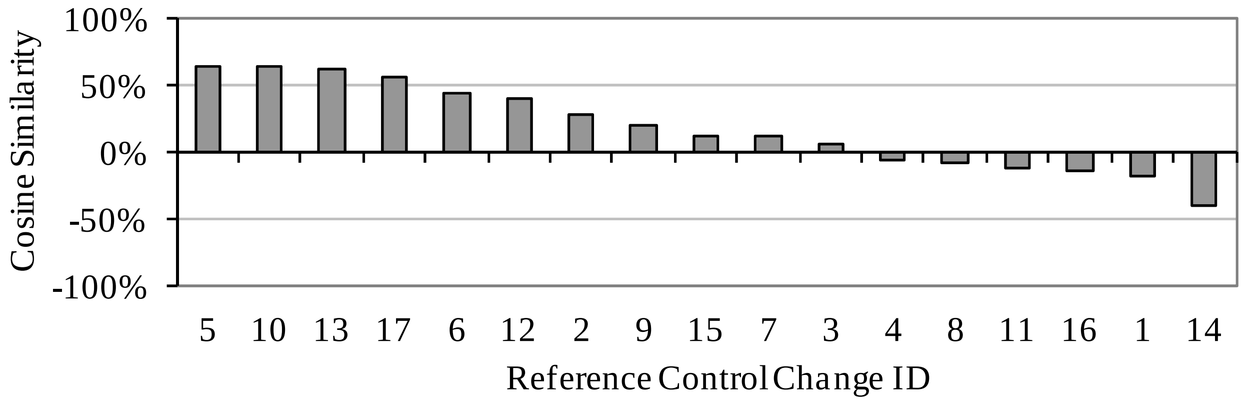


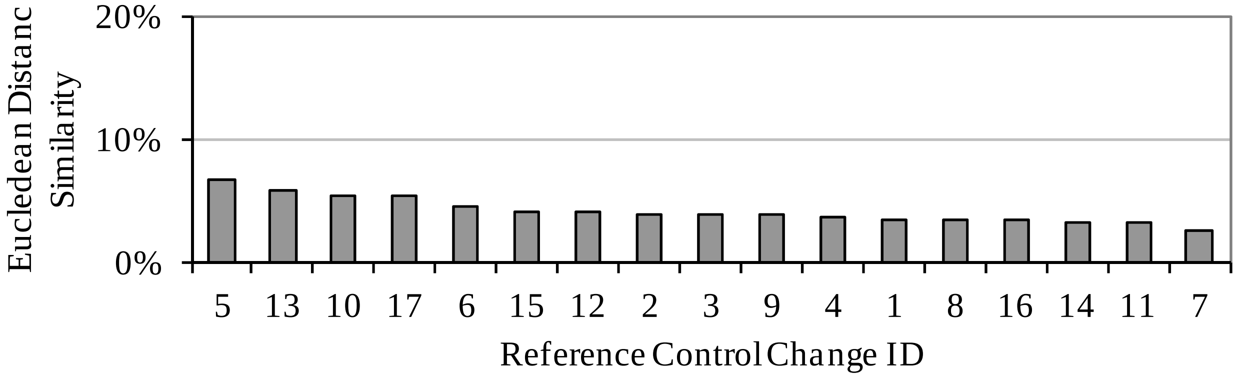
Reference Control Change Library

ID	Reference Control Change	Magnitude					Units
		I	II	III	IV	V	
1	X_{oa} decrease	-2%	-4%	-6%	-8%	-10%	
2	X_{oa} increase	2%	4%	6%	8%	10%	
3	T_{preh} decrease	-3	-6	-9	-12	-15	°F
4	T_{preh} increase	3	6	9	12	15	°F
5	PreHL increase	10	20	30	40	50	kBtu/hr
6	T_{cl} decrease	-2	-4	-6	-8	-10	°F
7	T_{cl} increase	2	4	6	8	10	°F
8	T_{hl} decrease	-2	-4	-6	-8	-10	°F
9	T_{hl} increase	2	4	6	8	10	°F
10	HL increase	10	20	30	40	50	kBtu/hr
11	X_{min} decrease	-2%	-4%	-6%	-8%	-10%	
12	X_{min} increase	2%	4%	6%	8%	10%	
13	T_{rc} decrease	-1	-2	-3	-4	-5	°F
14	T_{rc} increase	1	2	3	4	5	°F
15	T_{rh} decrease	-1	-2	-3	-4	-5	°F
16	T_{rh} increase	1	2	3	4	5	°F
17	TDL increase	2%	4%	6%	8%	10%	

Diagnosis Results

- Preheating valve leaking





5: Preheating valve leaking
10: Heating coil valve leaking
13: Room cooling set-point temperature decrease

Conclusions

- Developed new whole building fault diagnosis methods using cosine similarity and Euclidean distance similarity to identify the possible causes
  - Rank the possible fault causes according to their probability
- Both methods were used to investigate the reasons for two abnormal energy consumption faults in two real buildings
- Field test results suggest that the cosine similarity method and the Euclidean distance similarity method are promising techniques for whole building fault diagnosis

Questions?