Application of Automated Fault Detection and Diagnostics For Rooftop Air Conditioners in California

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ABSTRACT

The primary goal of the research described in this paper was to apply a decoupling-based fault detection and diagnosis (FDD) technique and economic assessment method to light commercial cooling and heating equipment in California. The paper describes the decoupling-based FDD methodology and the economic assessment method. The methods have been applied to a number of field sites. Detailed results are given for a single site and summary results are given for the other sites. About 70% of the investigated systems were impacted by faults and about 40% had more than one fault. Service was justified for about 40% of the units. The FDD technique was able to diagnose most of the existing faults. The estimated 10-year cost savings for FDD ranged from about \$800 to \$1700 per ton.

Introduction

Packaged air conditioning equipment is used extensively throughout small commercial and institutional buildings. However, compared to larger systems, they tend to be not well maintained. Widespread application of automated fault detection and diagnosis (FDD) to packaged equipment has the potential to significantly reduce energy use and peak electrical demand, down time and maintenance costs.

In the late 1980's, some researchers investigated common faults and methods for fault detection and diagnosis in simple vapor compression cycles, such as a household refrigerators. With the growing realization of the benefits brought by FDD, many more papers about HVAC FDD have appeared in the last ten years, more than 30 since 1999. According to the IEA ANNEX 34 final report (Dexter and Pakanen, 2001), twenty-three prototype FDD performance monitoring tools and twenty-six FDD tools have been tested in real buildings.

Rossi and Braun (1997) modified the general FDD supervision methodology first described by Isermann (1984) for non-critical HVAC system and developed a statistical rule-based (SRB) FDD technique for vapor compression air conditioners. Following this research, Breuker and Braun (1998a and 1998b) first identified important faults and their impacts on rooftop air conditioners through interactions with industry personnel, and then did a detailed laboratory evaluation of the performance of the SRB FDD technique for fixed-orifice systems. To keep track of the up-to-date research, Comstock, Chen, and Braun (1999) performed an exhaustive literature review of FDD in HVAC. This review provided a solid background and guide for later research. The fault characteristics for a system with a TXV are different from those with a fixed orifice for which Rossi and Braun originally developed the SRB FDD technique. Chen (2000) modified and evaluated the original SRB FDD technique for a 5-ton rooftop unit with a TXV as the expansion device.

Li and Braun (2002 and 2003) improved the sensitivity and robustness of the SRB method and reduced its computational requirements by developing a new on-line modeling approach and new detection and diagnosis classifiers. The resulting method is simpler to implement and was shown to have better sensitivity for detecting and diagnosing faults than the original method. However, it was not possible to modify the method to handle multiple-simultaneous faults, and the application of this method to field sites proved to be difficult because of the requirement for training models using field data. The method is better suited to implementation in original equipment than for retrofit to field applications.

Inspired by an effort to formulate model-based FDD techniques in a general mathematical way, Li and Braun (2004a) developed a decoupling-based FDD approach to handle multiple-simultaneous faults and eliminate the need for model training using field data. The ability to handle multiple faults was addressed by identifying features that decouple the impacts of individual faults. The need for on-line models was eliminated by employing manufacturers' rating data such as compressor and TXV maps (Li and Braun, 2004c). These data are readily available at no cost and are generic and reasonably accurate. The performance of the decoupling-based FDD method was initially tested using laboratory data. A prototype software implementation was developed and a demonstration was created for illustration purposes using the Purdue field site with faults artificially introduced. To evaluate the potential benefit for justifying service costs and FDD application, Li and Braun (2004b) also developed an economic assessment method associated with FDD.

The current paper first summarizes the decoupling-based FDD methodology and economic assessment method, and then presents an initial application to packaged commercial vapor compression equipment located in California.

Decoupling-Based FDD Technique and Economic Assessment Method

Decoupling-Based FDD Technique

Faults and system state variables (temperatures, pressures…) are strongly coupled. To handle multiple-simultaneous faults, the impacts of different faults on the system should be decoupled. That is, if one independent feature, which is impacted only by one fault, can be found for each individual fault, then multiple-simultaneous faults are decoupled. For a linearized system (see Equation (1)), a transformation matrix P can be found to diagonalize a transfer function matrix J, the linearized system model representation, to decouple the system if such a detailed system physical model is available. Before transformation, the FDD feature Y is a vector with different faults corresponding to different values of Y. After the interactions between the transformed FDD features Z and faults X (see Equation (2)) are decoupled, each entry of vector Z only corresponds to a unique fault entry of the fault vector X and vice versa. That is, transformed features are scalars. At this point, the SRB fault detection classifier developed by Li and Braun (2003) can be extended to handle multiple-simultaneous faults. The original $n-dimensional$ FDD problem has been decoupled to be n $1-dimensional$ SRB FDD problems. The decoupling-based classifying method simplifies fault detection from a high-D problem to n 1-D ones (see Equation (3)).

$$Y = JX \tag{1}$$

$$Z = PY = PJX = \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{bmatrix} X \quad (2)$$

$$\frac{(z_i - \mu_{i,normal})^2}{\sigma^2_{i,normal}} \underset{\omega_2 : faulty}{\overset{\omega_1 : normal}{\lesseqgtr}} (\chi^2)^{-1}\{(1-\alpha),1\} \quad (3)$$

where, λ_i are the transformed scaling factors, $\mu_{i,normal}$ and $\sigma_{i,normal}$ are the mean and standard deviation of feature z_i at normal operation, $(\chi^2)^{-1}\{,\}$ is the inverse chi-square cumulative distribution function, α is the false alarm rate, and $i = 1,2,\cdots,n$. Class ω_1, normal operation is selected if the left-hand-side is less than right-hand-side and class ω_2, faulty operation, is selected otherwise.

Fault diagnosis automatically is achieved without any extra computation immediately after fault detection is finished, so a fault diagnosis classifier is not required. This approach overcomes the primary drawback of the SRB diagnosis method in that it handles multiple-simultaneous fault diagnosis. The method is also more generic and system-independent than the SRB method and does not require complicated rules, which depend on the system type.

Mathematically, there exist an infinite number of decoupling features for steady-state operation. However, to obtain a detailed physical model taking faults into account for a rooftop unit system is extremely difficult and only those with intuitive physical meaning and those that are readily available (low-cost) are practical. Li and Braun (2004a) developed a methodology with guidelines to decouple the system, which unfolds the 'black-box' representing the rooftop unit system. This means that rooftop unit system is viewed from a microscopic point of view rather than treated as a system-level model relating inputs and outputs. Some independent features with physical meaning for component-level faults were found, and service faults were isolated from operation faults. There is an important and practical restriction for the independence features. They should be able to be expressed as functions of low-cost measurements such as temperatures and pressures.

Equation (4) formulates the decoupling scheme and results of all the rooftop faults that was developed. Each element of vector Z corresponds to one feature for one single fault in terms of residual, which is defined as the difference between actual value and normal value. Strengths about this method are that 1) normal values are readily available without the need of costly normal models and 2) actual values are obtained either directly by low-cost sensors or indirectly by virtual sensors based on low-cost measurements. For example, the normal value of the condenser air flow rate is the nominal value given by manufacturer while the actual value is estimated by an energy balance model, and the normal value of pressure drop across the filter/drier is zero in a statistical sense while the actual value is estimated by an expansion device model.

$$
\begin{bmatrix} \Delta T_{cond} \\ \Delta T_{dis} \\ \Delta^2 P_{ll} \\ \Delta \dot{m}_{ca} \\ \Delta \dot{m}_{ea} \\ T_{sh-sc} \end{bmatrix} = Z = LX = \begin{bmatrix} l_{11} & & & & & \\ & l_{22} & & & & \\ & l_{32} & l_{33} & & & \\ & l_{42} & & l_{44} & & \\ & l_{52} & & & l_{55} & \\ l_{61} & l_{62} & l_{63} & l_{64} & l_{65} & l_{66} \end{bmatrix} \begin{bmatrix} NonCond \\ CompLeak \\ LLRestr \\ CondFoul \\ EvapFoul \\ RefCharge \end{bmatrix} \tag{4}
$$

where, ΔT_{cond} is the temperature difference between the condensing temperature and saturated temperature based on condensing pressure, $\Delta \dot{m}_{ca}$ is condenser air mass flow rate residual, $\Delta \dot{m}_{ea}$ is evaporator air mass flow rate residual, $\Delta^2 P_{ll}$ is the liquid line pressure drop residual, ΔT_{sh-sc} is the difference between suction line superheat and liquid line subcooling, *NonCond* denotes non-condensable gas fault, *CompLeak* denotes compressor valve leakage fault, *LLRestr* denotes liquid-line restriction fault, *CondFoul* denotes condenser fouling fault, *EvapFoul* denotes evaporator fouling fault, and *RefCharge* denotes refrigerant charge faults including low charge and overcharge. Matrix L is sparse and lower triangular, which means that the system is unilaterally decoupled. That's, some faults are only decoupled in one way. For example, compressor leakage fault affects condenser fouling fault but does not vice versa. The equation can be solved without iteration as proposed by Li and Braun (2004a). Based on the decoupling residuals, the classifier described in Equation (3) can be applied to do FDD.

A demonstration prototype was made for Purdue field emulation site. Figure 1 shows the output at a point where four faults had been introduced. The bar chart in the upper-left quadrant shows individual fault indicators relative to a FDD threshold (0.2, corresponding to a 4% of capacity degradation), which is chosen based on the sensitivity of the method and economic necessity. Each of the fault indicators have been normalized so that full scale (i.e., 1.0) corresponds to an individual fault causing 20% degradation in cooling capacity. The graph in the lower-left quadrant shows impacts of the faults on performance and safety factors as a function of time during the demonstration. The factors include cooling capacity, COP, and overheating of the compressor. The capacity and COP are reductions relative to values for equipment operating normally. The compressor overheating is the difference between the current and normal compressor discharge temperature normalized by a value considered to be harmful to the compressor life. The table in the lower right quadrant summarizes the current values of the fault indicators and performance and safety factors. Also shown are current recommendations provided by the FDD method. The demonstration has been very useful in testing the FDD method for single and multiple faults and for illustrating the potential for application of FDD.

Economic Assessment Method

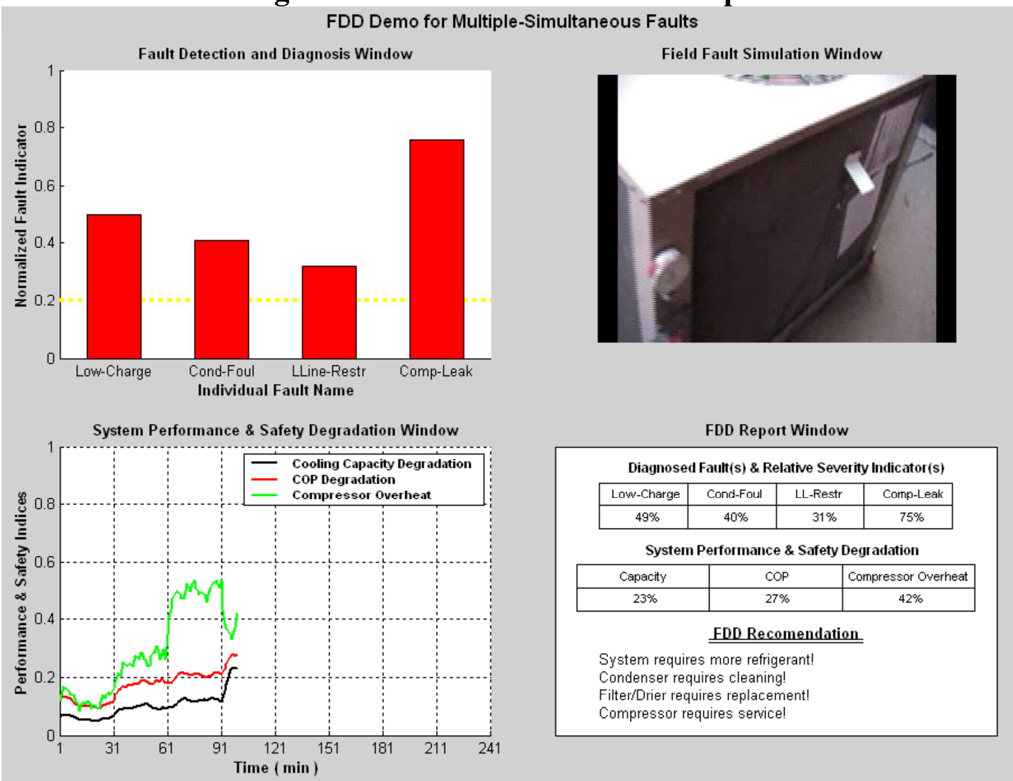
In contrast to critical systems, the primary consequences of faults in HVAC systems are economic rather than safety-related. Therefore, FDD systems applied to HVAC systems must be assessed based upon economic considerations. Li and Braun (2004b) investigated four major aspects of savings associated with FDD application to rooftop units (RTU) qualitatively and quantitatively. They include preventive maintenance inspection savings (PMIS), operational cost savings (OCS) including utility cost savings (UCS) and equipment life savings (ELS), fault detection and diagnosis savings (FDDS) including unnecessary service savings and fault diagnosis savings, and smart service schedule savings (SSSS). Savings are functions of various factors such as location, building type, application and system ratings. For example, UCS can be calculated from equation (5) and ELS are quantified as equation (6). The total OCS is the sum of UCS and ELS, which is especially important for justifying service as well.

$$UCS = \left(\frac{\alpha}{(1-\alpha)EER_{Normal}}\bar{\dot{Q}}_{Cap,Normal}(1-\beta)T\right)C_e \tag{5}$$

$$ELS = 0.0625 \cdot \bar{\dot{Q}}_{Cap,Normal}\frac{\beta}{1-\beta}T \tag{6}$$

where, EER_{Normal} is energy efficiency ratio under normal operation; α is the degradation in EER due to the faults, $\bar{\dot{Q}}_{Cap,Normal}$ is the normal cooling capacity; β is degradation in cooling capacity; C_e is the cost of electricity ($/kWh); and T is the actual runtime.

Figure 1. FDD Demonstration Output



Field Application to Packaged Commercial Equipment in California

Description of California Sites

All the field-sites in California are small commercial buildings that utilize packaged air conditioning and heating equipment. The criteria used for selecting the field-sites included: 1) building occupancy type and size; 2) HVAC system installed, and 3) climate region. The types of buildings include smaller retail stores, play areas for fastfood restaurants and modular schoolrooms. The HVAC systems installed include different rooftop and wall mounted units with different capacities and from different manufacturers. The climates include two different macroclimate types: coastal and inland. The following system state variables were measured: high and low-side pressures, suction and discharge line temperatures, evaporating and condensing temperatures, liquid line temperatures before and after filter/driers, condenser inlet and outlet air temperatures, return and outdoor and supply air temperatures, return and outdoor air humidities, and current and voltage and power consumption of the compressor.

Application of FDD to a Fastfood Restaurant Play Area

This site is located in Oakland, California. A 6-ton rooftop unit was installed for the play place of the fastfood restaurant. A scroll compressor and a TXV are used in this RTU. Data collected from April to October in 2002 were used to perform FDD. After filtering the transient data by a steady-state detector and removing the bad data corrupted by the acquisition equipment, 1119 data points (one data point every five minutes) were retained. Since the RTU has been installed for several years, faults have been fully developed. Statistical results are presented in terms of histogram bar plots.

Figure 2 shows normalized fault indicators for the five different faults considered in this study. Figure 2a gives normalized fault indicators for a liquid-line restriction fault. All the steady-state data points are located at the right of the red dotted FDD threshold line and the mean value is around 0.8. That is, all steady-state points indicate that the liquid-line was restricted. Most likely the filter or drier was clogged by debris. If this fault happened individually, it would result in about a 16% cooling capacity degradation.

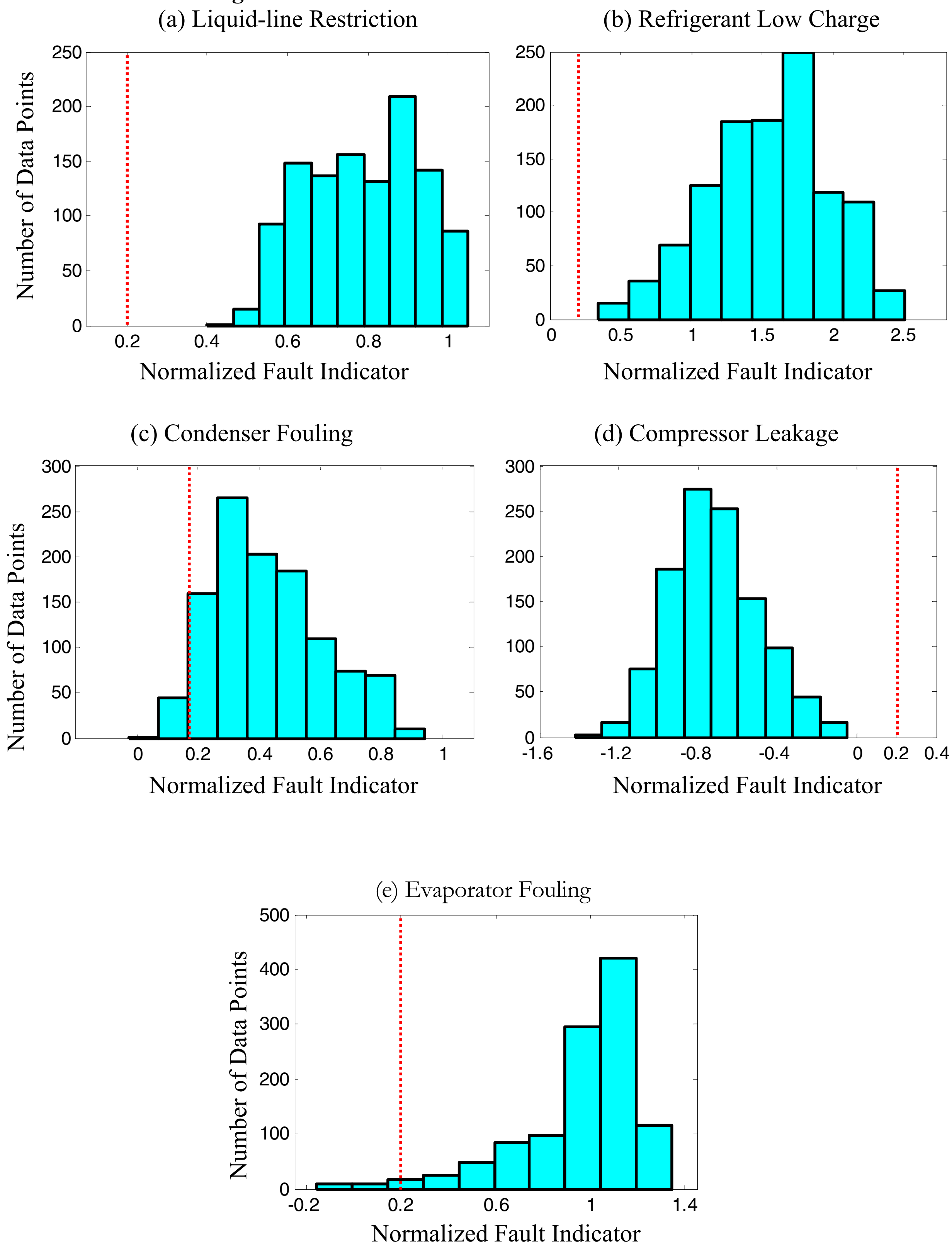
Figure 2b plots the normalized fault indicator for refrigerant charge faults. Similar to Figure 2a, all the steady-state data points are located to the right of the FDD threshold and the mean value is about 1.6, which means that the system charge was very low. If this fault happened individually, it would result in about a 32% cooling capacity degradation.

Figure 2c plots the normalized fault indicator for a condenser fouling fault. Most of the steady-state data points (>95%) are to the right of the FDD threshold and the mean value is about 0.5, which indicates that the condenser was a little dirty. If this fault happened individually, it would result in about 10% cooling capacity degradation.

Figure 2d plots the normalized fault indicator for a compressor valve leakage fault. All the steady-state data points are to the left of the FDD threshold and the mean value is about -0.7, which indicates that the compressor worked properly and the compressor had about 15% heat loss. However, according to heat transfer analysis and our experience with laboratory data, compressors installed in packaged RTUs have very small heat loss, less than 5% of the power input and even gain some heat at some operating conditions. The explanation for this discrepancy is probably that the discharge line temperature is not measured accurately using the RTD temperature sensor. Braun and Li (2003) investigated the RTD measuring issue and presented a correction approach. However, there is evidence that the discharge line temperature sensor was not probably installed or insulated.

The normalized fault indicator for the evaporator fouling fault is plotted in Figure 2e. Most of the steady-state data points are at the right of the FDD threshold and the mean value is

Figure 2. Normalized Fault Indicators for Different Faults



about 0.96, which indicates that the evaporator was dirty. If this fault occurs individually, it would result in about 19% cooling capacity degradation.

In summary, the system had four simultaneous faults, low refrigerant charge, liquid line restriction, condenser fouling and evaporator fouling.

Economic Savings Assessment for the Fastfood Restaurant Play Area

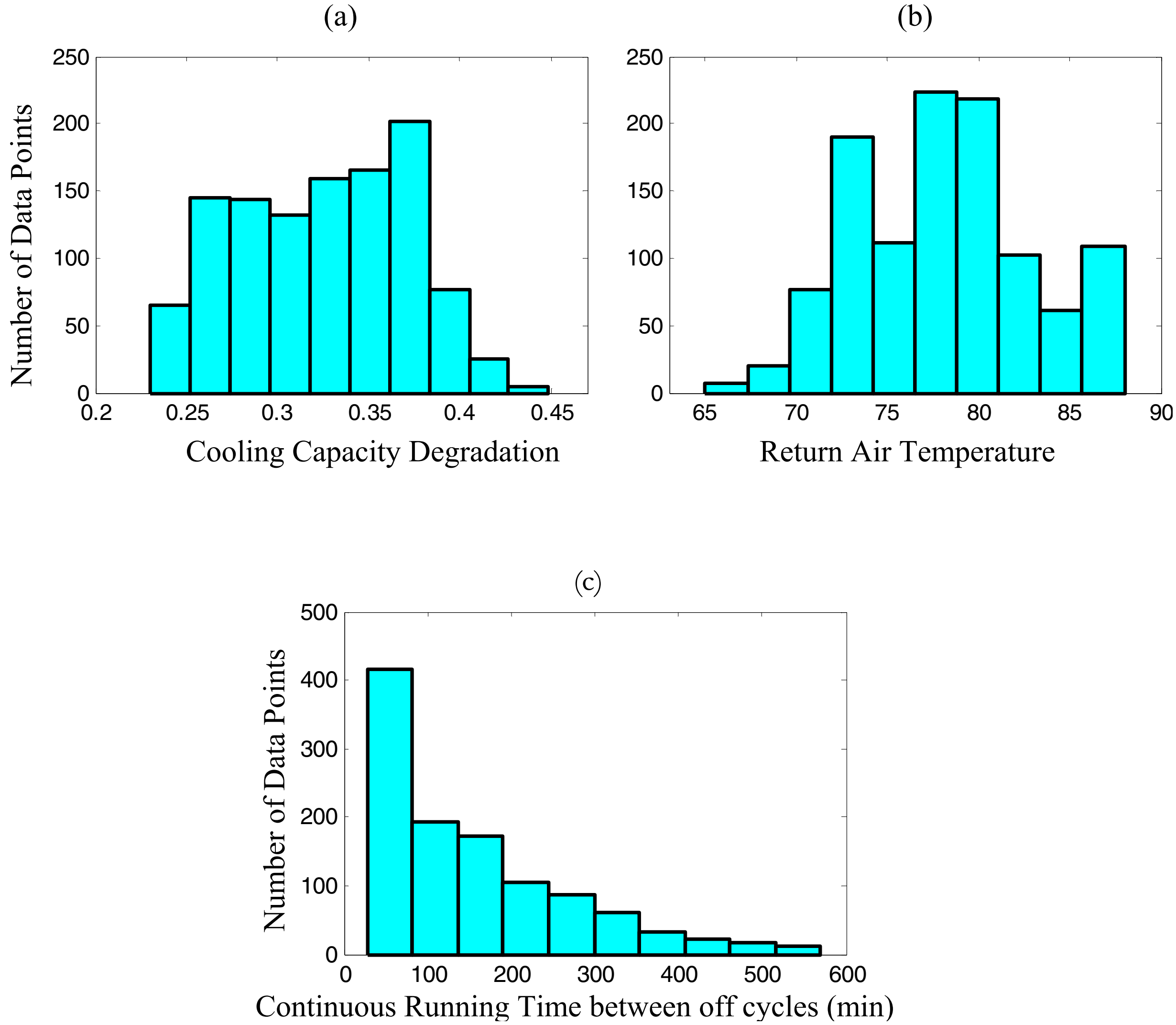
Figure 3a plots the cooling capacity degradation associated with the combination of these faults for the case study site. The system cooling capacity was degraded 23~45% (average of about 32%), which was consistent with the value indicated by the refrigerant charge fault indicator. The low charge fault is a system-level fault which is not completely decoupled from other component-level faults and thus its indicator reflects the impact of other faults. The cooling capacity degradation is consistent with the return air temperature and system running time. It can be seen from Figure 3b that the average return air temperature was around 78 F and the highest was 88 F, which means that this equipment did not maintain comfortable space conditions much of the time. From Figure 3c, it can be seen that the system ran continuously for a long time (average of 2.5 hours, maximum of 9 hours). So, based on a comfort criterion, service should have been done to correct the diagnosed faults.

Figure 4a plots an economic criterion for service, EER degradation. It can be seen that the system EER degraded between about 10~40%, depending on the operating conditions. Compared with the cooling capacity degradation, the EER degradation was a little smaller. Figure 4b plots the system power consumption reduction. The average power consumption reduction was about 15%, which was smaller than the average cooling capacity degradation (β) of 32%. The average degradation in EER (α) was 21%. Roughly, the weighted average utility rate (C_e) between on-peak and mid-peak periods in North California is 0.08$/kWh. For this restaurant application in North California, the average runtime was 900 hour/year.

With automated FDD, it is estimated that direct operational cost savings (OCS) for this site would be about $252/year with UCS of $107/year and ELS of $145/year. This estimate does not consider the direct impact of faults on reducing the runtime before failure of the compressor, but only their impact on life due to an increase in runtime. It would cost about $1000 to replace the compressor in this air conditioner, so this could be an important effect that is not considered. Service costs to add some refrigerant, replace the filter/drier, and clean the heat exchanger coils would be around $500 if they were performed in one trip. Based upon the OCS alone, the economic payback for service to correct the faults would be around 2 years. Thus, service appears to be justified based upon both comfort and economic criteria for this case study.

There are some other significant savings associated with the application of automated FDD that need to be considered in evaluating overall economics. For a single RTU, the following estimates were obtained using data from service providers: PMIS of $203/year, FDDS of $137/year, and SSSS of $70/year. PMIS comes from reduction of costly preventive maintenance visits. Application of automated FDD would reduce or eliminate the costly and time-consuming manual diagnostic time. For this particular case study, it would be difficult for an experienced technician to identify all four faults in one visit without the help of an automated FDD system. It is estimated that smart service scheduling for multiple faults would contribute about $70/year in savings. The total estimated savings associated with the application of automated FDD to this site would be about $662/year. It appears that this level of savings would provide reasonable paybacks for implementation of automated FDD.

Figure 3. Capacity Degradation, Return Air Temperature, and Runtime Distributions



Summary Results for Other Sites

Since the sites in California were originally configured for application of the SRB technique, some necessary information about the compressor, expansion device and system configuration were not available for application of the FDD method discussed in this paper. Therefore, the FDD technique was only partially applied to the other sites. Similar to Oakland fastfood restaurant site, data collected from April to October in 2002 were used to do analysis for the following sites except for the Anaheim retail store site, which is based on data collected in 2003.

The diagnosis results for these sites are summarized in Tables 1, 2, 3 and 4. In summary, the initial investigation shows that faults happen very frequently at the field sites. Fifteen of the twenty-one systems (71%) are significantly impacted by faults: eleven (52%) have filter/drier restrictions, ten (48%) have refrigerant charge faults, eight have (38%) have more than two simultaneous faults and nine (43%) justify service immediately.

Figure 4. EER Degradation and Power Consumption Reduction

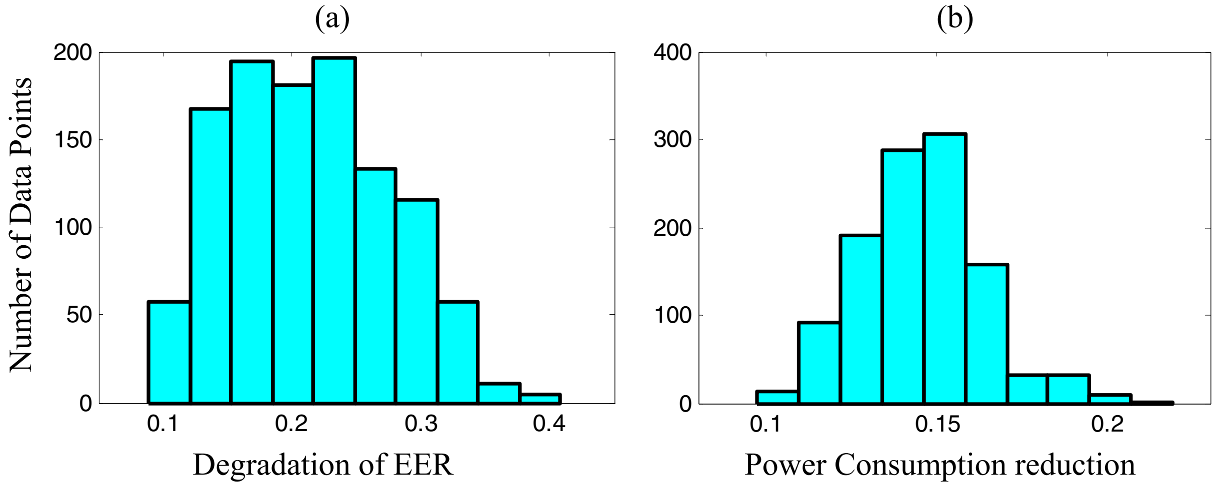


Table 1. FDD Results for Modular School Sites

	Woodland		Oakland	
	RTU1	RTU2	RTU1	RTU2
Refrigerant Charge	Normal	Normal	Normal	Over
Liquid-line Restriction	Yes	Yes	Yes	No
Evaporator Fouling	No	No	No	Yes
Service	Not yet	Yes	Not yet	Yes

Based on the statistical assumptions made by Braun and Li (2004), the lifetime total savings per ton are summarized in Table 5 for all different types of applications and locations. The estimated savings over the 10-year life of the unit range from \$800 to \$1700 per ton. Greater savings are possible in hotter climates (South California) due to larger cooling requirements and higher utility rates. The savings would be greater for heat pumps because they operate throughout the whole year.

Conclusions

A decoupling-based FDD technique and economic savings assessment method were applied to packaged air conditioning equipment at California field sites. Initial investigation shows that faults occurred frequently at the field sites, which was confirmed by a recent site visit. The FDD technique was able to diagnose most of the existing faults even with limited information. The potential yearly cost savings associated with application of the FDD technique are significant, ranging from \$80 to \$170 per ton. The preliminary estimation of implementation costs of the FDD technique approximately ranges from \$250 to \$600 per system for individual application and \$175 to \$375 for multiple applications. So, for a middle-sized RTU (say 6-ton), the yearly savings would range from $500 to $1000 and would appear to provide reasonable payback periods for implementation.

Table 2. FDD Results of Play Areas in Fastfood Restaurant Sites

	Brad-shaw	Castro Valley		Watt Avenue	
		Stage 1	Stage 2	Stage 1	Stage 2
Refrigerant Charge	Low	Normal	Normal	Low	Normal
Liquid-line Restriction	Yes	No	No	No	No
Service	Yes	NA	NA	Not	NA

Table 3. FDD Results for Retail Store Sites at Rialto

	RTU1	RTU2	RTU3	RTU4	RTU5
Refrigerant Charge	Low	Low	Normal	Normal	Over
Liquid-line Restriction	No	Yes	No	No	No
Service	Yes	Yes	NA	NA	No

Table 4. FDD Results for Retail Store Sites at Anaheim

	RTU1	RTU2	RTU3	RTU4	RTU5
Refrigerant Charge	Low	Low	Normal	Low	Normal
Liquid-line Restriction	Yes	Yes	Yes	Yes	Yes
Service	Yes	Yes	Not yet	Yes	Not yet

Table 5. Estimated Lifetime Total Savings per Ton of Cooling (based on a 6-ton RTU)

Location	Building Type	PMIS ($)	OCS ($)	FDDS ($)	SSSS ($)	TELS ($)
North California	Modular School	338	89	228	167	822
	Restaurant		168			901
	Retail Store		335			1068
South California	Modular School		284			1017
	Restaurant		497			1230
	Retail Store		994			1727

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References

Braun, J.E. and Li, Haorong. 2003. "A Decoupling-Based FDD Approach for Multiple-Simultaneous Faults". Progress report submitted to Architectural Energy Corporation.

Braun, J.E. and Li, Haorong. 2004. "Automated Fault Detection and Diagnostics of Rooftop Air Conditioners for California". Final report submitted to Architectural Energy Corporation.

Breuker, M.S. and Braun, J.E., 1998a. "Common Faults and Their Impacts for Rooftop Air Conditioners", HVAC&R Research, Vol. 4, No. 3, pp.303-318.

Breuker, M.S. and Braun, J.E., 1998b. "Evaluating the performance of a Fault Detection and Diagnostic System for Vapor Compression Equipment", International Journal of Heating, Ventilating, and Air Conditioning and Refrigerating Research, Vol. 4, No. 4, pp.401-423.

Chen, Bin, 2000a. "Evaluating the potential of on-line fault detection and diagnosis for rooftop air conditioners", Master's Thesis, School of Mechanical Engineering, Purdue University.

Comstock, M.C., J.E. Braun, and B. Chen, 1999, "Literature Review for Application of Fault Detection and Diagnostic Methods to Vapor Compression Cooling Equipment", Purdue University, Ray W. Herrick Laboratories, Report # HL99-19.

Dexter, Arthur; Pakanen, Jouko (ed.). "Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings". VTT Building Technology, 2001. VTT Symposium 217. 381 p. + app. 13 p.

Isermann, R. 1984. "Process Fault Detection Based on Modeling and Estimation - A Survey", Automatica, 20(4): 387-404.

Li, H. and Braun, J.E. 2003, "An Improved Method for Fault Detection and Diagnosis Applied to Packaged Air Conditioners". ASHRAE Transactions, Vol.109, Part 2.

Li, H. and Braun, J.E., 2002, "On-Line Models for Use in Automated Fault Detection and Diagnosis for HVAC&R Equipment," Proceedings of the 2002 ACEEE Conference on Energy Efficiency in Buildings, Monterey, CA, 2002.

Li, H. and Braun, J.E., 2004a, "A Methodology for Diagnosing Multiple-Simultaneous Faults in Rooftop Air Conditioners". Accepted for the Tenth International Refrigeration and Air Conditioning Conference at Purdue to be held on July 12-15, 2004.

Li, H. and Braun, J.E., 2004b, "An Economic Evaluation of Automated Fault Detection and Diagnosis for Rooftop Air Conditioners". Accepted for the Tenth International Refrigeration and Air Conditioning Conference at Purdue to be held on July 12-15, 2004.

Li, H. and Braun, J.E., 2004c, "Modeling Adjustable Throat-Area Expansion Valves". Accepted for the Tenth International Refrigeration and Air Conditioning Conference at Purdue to be held on July 12-15, 2004.

Rossi, T.M. and Braun, J.E., 1997. A Statistical, Rule-Based Fault Detection and Diagnostic Method for Vapor Compression Air Conditioners, International Journal of Heating, Ventilating, and Air Conditioning and Refrigerating Research, Vol. 3, No. 1, pp.19-37.