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Investigations of faulty interaction effect to refrigeration system operations

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Abstract. Supermarkets are the coupled system integration between HVAC (heating, ventilation and air-conditioning) and refrigeration systems in terms of interaction. The zone conditions provided by HVAC are used as the driving forces conditions for refrigeration load design to size proper compressor load. However, most of supermarket operators seldom understand the faulty interaction effect; faulty indoor conditions cause excessive power consumptions of refrigeration systems even they are operated efficiently because they are operated at wrong design conditions. The interaction effect is challenging issue in modern energy audit since both software and low-cost wireless sensors are more helpful to efficiently investigate any effect. Especially, faulty indoor interaction is not considered and still infancy in developing counties. This current paper present faulty interaction affecting to refrigeration system operations by utilizing data from building automation systems from supermarkets in the U.S. The method is simply developed to examine faulty interactions and the effect. The findings are that detected faulty operations lead to excessive power consumptions. Without the consideration, fault detection and diagnosis (FDD) performance is degraded and mistaken due to wrong conditions in analysis for refrigeration systems. The method can be further used by building operators or building auditors as easy-to-use tool for integrated system investigations.

Introduction

Although energy audit programs have been developed and proposed for mainly improving system performance to achieve energy savings in supermarkets, refrigeration systems have practically been analyzed without considering the effect of faulty operations provided by heating, ventilation and air-conditioning (HVAC) systems; these effects result in waste energy consumptions. For the correlation of HVAC and refrigeration systems, refrigeration condenser cooling load used for HVAC sizing is excluded when the condenser unit is located outside a store. In contrast, if the condenser is within the building, the heat rejection of the indoor condensers will increase the cooling load of the store HVAC system. As a consequence, the HVAC system can no longer maintain the indoor design conditions; these faulty indoor conditions cause excessive power consumptions in the HVAC system. This correlation is called "energy interaction [1]".

Even though the interactions in supermarket environment have been significantly concerned more than two decades using computer simulations, laboratory tests, and field evaluations [e.g., 2 – 11], most of the previous researchers mainly conducted for sub-system performance evaluations, machine design improvements and refrigeration system replacement and retrofitting. No prior research paper has been completely proposed the faulty interaction analysis for enhancing fault detection and diagnosis (FDD) on refrigeration systems used by building operators, facility management companies and/or HVAC&R analysts.

For example, Henderson and Khattar [12] analyzed humidity impact of refrigeration operations in two supermarkets. The simplified power consumption model based regression analysis was proposed; the findings are seldom used in practice beyond the researches and ASHRAE standard. In addition, Kosar, and Dumitrescu [13] reviewed and synthesized supermarket potential savings versus humidity ranges published in the ASHRAE Handbook [3]. Presently, ASHRAE RP 1467 [14] was proposed to further analyze what factors affect energy savings of refrigeration energy consumptions when indoor relative humidity is reduced. In the project, the factor analysis is used to analyze the balancing latent heat load between refrigeration display cases and indoor conditions provide by HVAC systems. The most dominant factors in accomplishing energy savings in refrigeration energy consumptions are refrigeration capacity, case layout and lineup; these research findings are very helpful to support supermarket layout design for conducting low energy use.

To enhance this practical engineering point of view and reduce the aforementioned limitation in terms of inadequate HVAC&R operation data, this present article focuses on non-invasive and plug-n-play solutions via utilizing the existing BAS system of each store for energy interaction investigations. With the obtained data, an improved energy interaction method based on typical control operations, user-friendly statistics and rule-based method is proposed as a simple tool for the performance investigations of HVAC&R operations in supermarkets. The improved method includes the investigations of faulty interaction effect to refrigeration system operations.

Backgrounds

2.1 Typical energy audit and analysis in commercial buildings

According to the survey of commercial energy audit reports and research papers, building energy model toolkit as a benchmarking tool was developed for energy modeling used to evaluate baseline energy of each commercial building under ASHRAE research project RP-1050 [15]. In the graph analysis, outdoor air temperature (OAT) and energy consumptions are used to construct simple linear regression (SLR), polynomial, logistic, and other types of models. One of the most intensively used models is SLR which can be further improved by using a change-point linear regressions in case of special routine operations are considered.

In case of practical energy audit for evaluating HVAC machine operations, OAT as the independent variable is used to notice stage operations of chillers because OAT increase is proportional to higher energy consumptions. For the multi-stage operations, in case of setting a constant set-point for evaporator water temperature, OAT is proportional to compressor percent load. Therefore, multiple lines can be plotted when OAT or percent load of compressors increases versus increased power consumptions [16]. However, for coupled system such the supermarket environment interaction, indoor air relative humidity (IARH) and zone air temperature (ZAT) are both driving force conditions of refrigeration compressors. As a result, the typical energy audit method is not potential enough to analyze the faulty interaction effect to refrigeration systems. This issue is challenged to improve the simple interaction method [1] which is briefly explained in next section.

2.2 HVAC and refrigeration systems in commercial supermarkets

The effect of HVAC operations to refrigeration systems is the interaction. When HVAC systems are not properly operated beyond the indoor design conditions, the refrigeration compressor unit (RCU) will consume higher energy consumptions. For instance, an indoor temperature at 75°F (24° C) with 75% RH for refrigerated cases, this relative humidity is out of the range from 35 to 50%, so higher latent load of indoor air results in higher energy consumptions for refrigeration compressors. Following this reason, the refrigeration system operations can be evaluated by considering the interaction of these two systems in supermarkets as depicted in Figure 1 and 2.

The typical zones in commercial supermarkets haves the layout as shown in Figure 1 in which temperature and humidity sensors are installed to measure the zone interaction at medium temperature display cases (sensor No. 1) and low-temperature display cases (sensor No. 2). Meanwhile, sensor No. 3, No. 4 and No. 5 are utilized to measure outdoor conditions, the supply temperature of air-conditioning operations for medium- and low-temperature display cases, respectively.

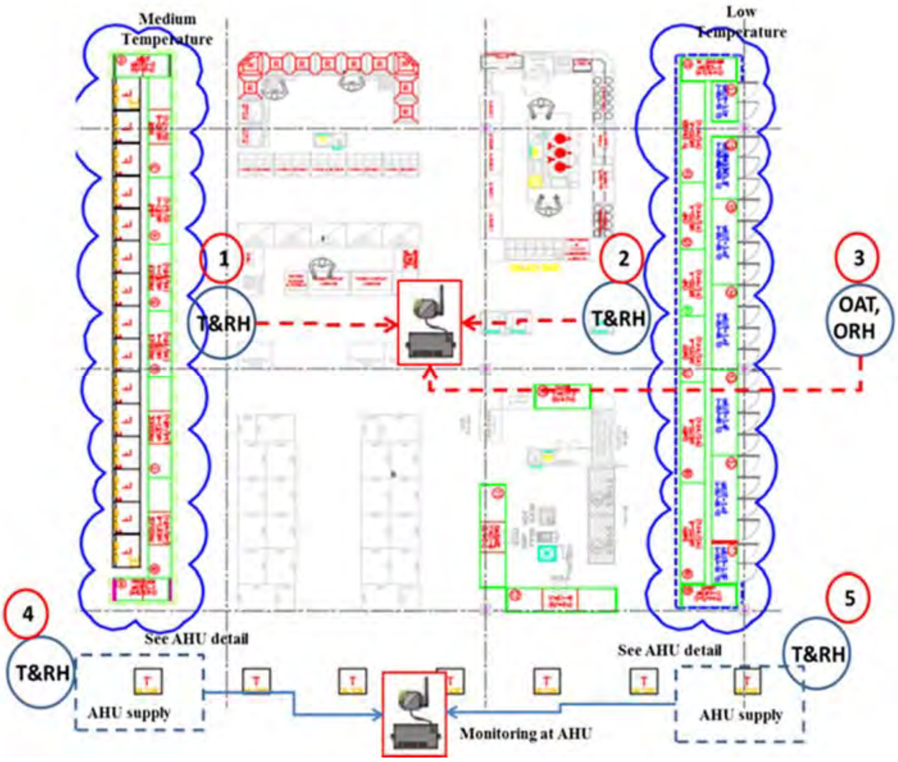

Figure. 1 Commercial supermarket layout

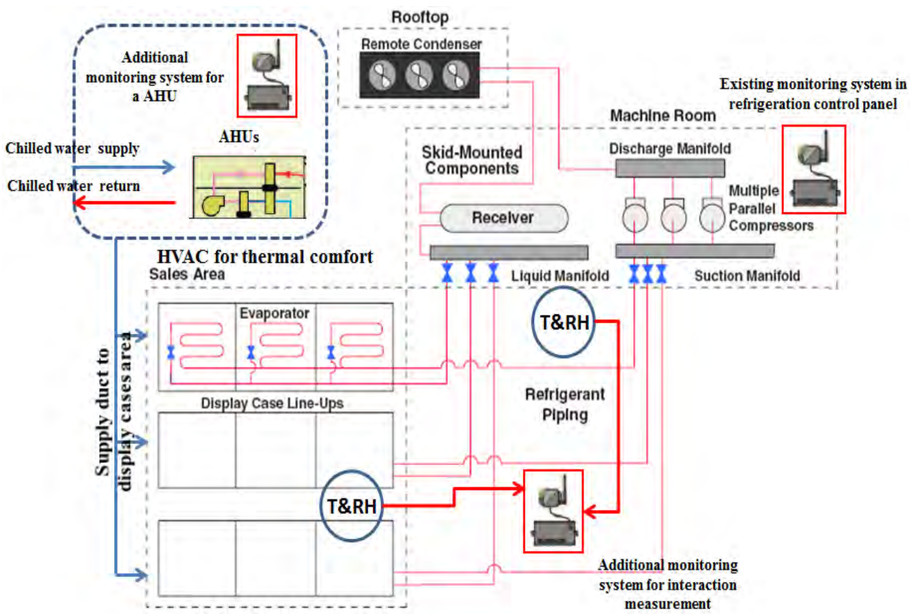

Figure 2. Simplify multiplexed refrigeration and HVAC systems

In commercial supermarket systems in Figure 2 for this research, the refrigeration system is practically designed as multiplexed direct expansion (DX) equipment including: 1) the condenser on a rooftop; 2) the multiple compressors with a liquid-line receiver located in a machine room; 3) evaporators installed in display cases at a sale area and 4) refrigerant piping system is utilized for supplying a refrigerant volume from the liquid manifold and receiver, which collect liquid refrigerant after it exits from the rooftop condenser. For Thai hypermarket, centralized refrigerant system or multiplexed DX system is multiple compressor operations in terms of compressor racks in a machine room; this type is used only in big cities in Thailand, not used in upcountry areas because experienced technicians are not enough for hard services or maintenances. Therefore, each self-contained unit is separated the condenser out for reducing over refrigeration machine loads; one large condenser is used as heat exchanger for all modified self-contained units

2.3 Simple Energy Interaction Overview

According to the simple energy interaction in Ref [1], the data inputs of the flowchart implementation include independent variables and a dependent variable (energy consumptions of each machine). The specific inputs and outputs are used to compute Pearson's correlation coefficient (R-value). By comparing the computed R-value to the expected range in Table 1 [1], normal machine operations can be identified in case of the computed R-values being in the expected range. In contrast, when the R-value shows lower correlation than the expected range or opposite correlation, an abnormal operation is specified.

Although this flowchart seems to be easy-to-use for HVAC&R performance investigations, it still lacks of accurate performance investigations and a guideline for auditors. Some issues are not considered: 1) stage-off operations are excluded to isolate active control operations from off-time control; 2) the method cannot potentially identify faulty energy signature in case of poor controllers; 3) outliers which dominantly affect data trend cannot be specified whether they are occurred by poor controllers or unsuitable set-points; 4) faulty operations affecting refrigeration systems are not considered; 5) operations of occupied and unoccupied periods are not included for the analysis; and 6) the method cannot isolate OAT influence from IARH or ZAT effect. With the aforementioned limitations, R-value applied in refrigeration systems could be mistaken.

Table 1. Expected R-values of interaction between HVAC&R energy consumptions and the independent parameters [1]

The R value of the interaction between power consumption and	Independent parameters in the interaction		
	OAT	IARH	ZAT
Rooftop unit (RTU)	Medium	Low	Medium
Dehumidification unit (DHU)	Medium	Medium	Low
RCU	Medium	Medium	Medium
Anti-sweat heater (ASH)	Low	High	Low

Note: low (0-0.50), medium (0.51-0.89) and high R value (0.9-1.0)

3. Energy Interaction Procedures

3.1. Step 1 Information collection in analysis

In this step, since OAT and ZAT sensors are both embedded into each RTU controller linked to BAS sever, they can be remotely downloaded from any places.

3.2. Step 2 RTU analysis

The three issues are required to be analysed in this step including: 1) normal trend of the active set-point control; 2) scatter plot of energy consumption caused by poor controller performance; and 3) different set-points in different periods based on monthly, weekly and daily analysis for assuring that the scatter data are not caused by the poor controller. The improved interaction can be overviewed and depicted in Figure 3 and the procedures are as follows:

3.2.1. *Step 2.1* is the procedure for a selected machine and driving force conditions of HVAC machines based on whole data.

3.2.2. *Step 2.2* uses the set-point or driving force of each machine to isolate baseline energy from the on-time control function areas. In this step, OAT at the critical point (intersection between 2 lines) leads to increased RTU energy consumptions which are proportional to OAT increase.

3.2.3. *Step 2.3* is to compare the computed value from step 3.3.2 to the expected values in Table 1. This stage operation identification can improve R-value performance.

3.2.4. *Step 2.4* is to identify outliers in case of obtaining lower R-values than the expected range in Table 1. Set points are useful to assure that outliers or scatter data are caused by different set-points in different periods.

3.3. Step 3 faulty operation effects

Due to ZAT and IARH values controlled by RTUs and DHUs, respectively, even though ZAT is proportional and dependent to OAT, ZAT is significant to notice the control set-points and control performance. As a result, the three variables (OAT, IARH and ZAT) are required to notice the interaction of refrigeration systems. To enhance the analysis, the improved method is developed based on the technique which was proposed by Henderson and Khattar, [12]; in this method, several IARH ranges are fixed within 10 %RH such as 30-40% and 40-50%. Then, OAT or ZAT is used as an independent variable of HVAC&R energy consumptions at a fixed 10% RH range.

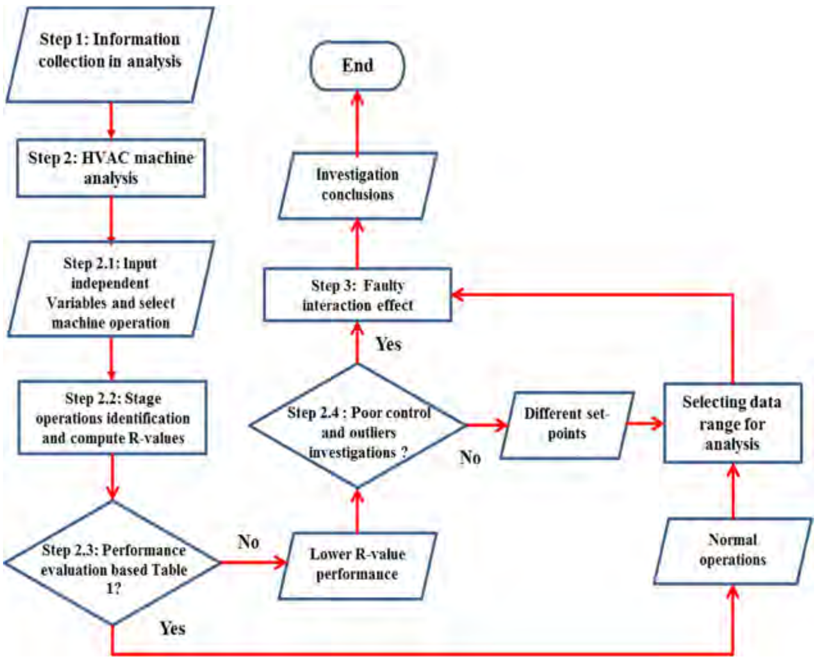

Figure 3. Improved energy interaction method with rule-based performance identifications

4. Results

4.1. Step 1

The stores are operated 24 hours a day and 7 days a week. The equipment is very similar at each location because all locations are the same retailer. The measurement data were obtained from the building automation systems (BAS) of 5 supermarkets located at different climates in the U.S.A. The data including power consumptions of equipment, OAT, IARH and ZAT were obtained from 3/3/2011 to 11/30/2011 as tabulated in Table 2.

Table 2. Information of measured data obtained from BAS [1]

Supermarket	DOE Climate Classification	IARH Range (%)	OAT Range, °F (°C)	ZAT Range °F (°C)
A	6A	20 - 63	50 (10) – 90 (32.2)	61 (16.1) -72 (22.2)
B	7A	25 - 70	42 (5.6) – 99 (37.2)	67 (19.4) – 75 (23.9)
C	3A	45 - 54	69 (20.6) – 105 (40.6)	69 (20.6) -74 (23.3)
D	5A	27 - 50	51 (10.6) – 88 (31.1)	72 (22.2) -75 (23.9)
E	3B	23 - 62	42 (5.6) – 87 (30.6)	66 (18.9) – 75 (23.9)
Meter recording	Power consumptions of RTU, DHU, Refrigeration compressor rack and ASH are recorded every 15 minutes in five locations			
Floor Area	100,000-125,000 sq. ft.			

4.2. Step 2

4.2.1. *Step 2.2.1* is to select RTU energy consumptions and OAT for the analysis in store A which is similar to the typical energy signature [15]. Also, DHU energy consumptions and IARH can be used to conduct multi-stage operation identifications, but not considered in this paper.

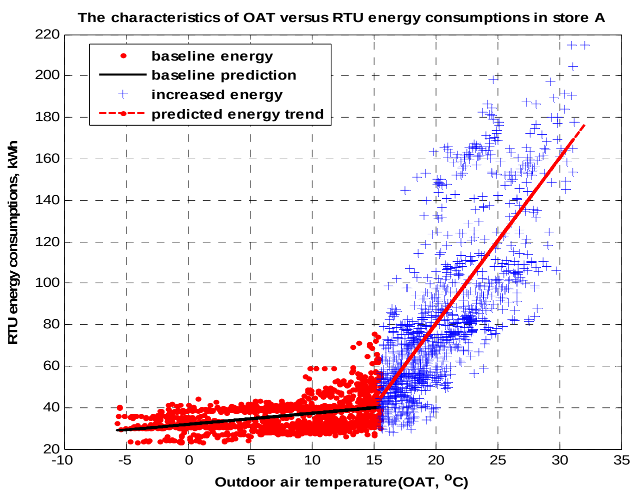

Figure 4. Normal operations of RTU energy consumptions versus OAT in store

4.2.2. *Step 2.2.2* is to demonstrate the example for RTU analysis in store A. With the preliminary plot between RTU energy consumptions and OAT as shown in Figure 4, it shows the typical two energy lines of RTU operations consists of baseline energy and increased energy line. The first line is the fan energy consumptions since minimum ventilation airflow rate is required for store occupants. In this line operation, the RTU compressor is still stage-off because the ZAT does not reach the set-point temperature. Whenever OAT is more than 15.6 °C approximately, the RTU compressor is initially staged on. As a consequence, the energy consumptions are proportionally increased to higher OAT values. With the apparent energy areas between off-time and on-time periods of the RTU control, the active controller area is computed for R-value .With the confidence at 0.05 ($p < 0.05$), the improved R-value of RTU energy consumptions and OAT is 0.755 given in Table 3.

4.2.3. *Step 2.2.3* is to compare the computed value from step 3.3.2 and to compare with the results obtained from the simple interaction method. All preliminary analysis of the improvement is resulted in Table 4.

Table 3. R-values between the three independent variables and RTU energy consumptions

RTU in store A	OAT	IARH	ZAT
Improved method	0.755 (N – active control)	0.135 (N)	0.597 (N – 2 stage)
Ref [1]	0.742 (N)	0.434 (N)	0.692 (N)

Note: F refers to faulty operations, whereas N symbol refer to normal operations

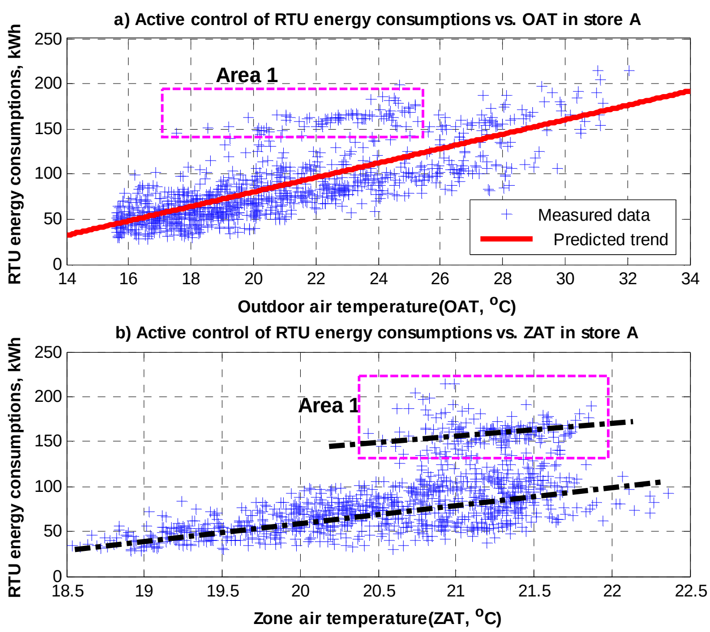

Figure 5. R-value improved based on computing active control data

4.2.4. **Step 2.2.4** is to identify outliers after energy consumption signature of each machine is identified. From Figure 5, it seems to notice several outliers deviated from the trended single line. It is possible that the system includes two-stage operations. To recheck the result, the new R-value is estimated versus ZAT using the same data; it is evident that some outliers are caused by the two-stage operations as depicted in Figure 5 (Area 1).

Regarding Figure 6, both ZAT and OAT can be used to identify outliers. To notice how control performance is, at small different set-points, large energy consumptions are consumed differently at the same sampling rate. Moreover, the RTUs at OAT values between 10 °C and 18.33 °C in the area should consume energy around 10 kWh; however, the RTUs consume from 20 to 50 kWh because the ZAT could be set in the dead band zone. The analysis can assure that the RTU controllers are poor performance.

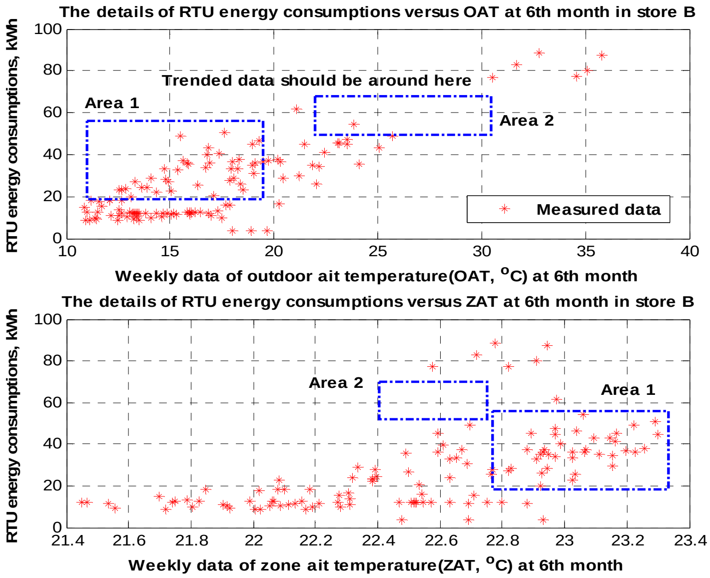

Figure 6. weekly data analysis example in store B

4.3. Step 3 faulty operation effects

To demonstrate this step clearly, the data in store E are used to show how poor operations of HVAC system affect refrigeration energy consumptions and operations. The IARH ranges are divided in 20-30%, 31-40%, 41-50% and the rest of the data.

In Figure 7, IARH ranged from 41 – 50% RH, poor control range occurs due to scatter points of ZAT between 21.67 and 22.78 °F and OAT between 12.78 and 21.11 °F. In the rectangle areas of Figure 7a and 7b, it is evident that the stage operation cannot be identified.

With the two intercept data between RCU energy consumptions versus ZAT and RCU energy consumptions versus OAT based on the identified faulty operations in Figure 7, ZAT provided by HVAC and the OAT range operations are used to locate energy consumptions of the RCU versus ZAT range in Figure 8. In the figure, it seems that the predicted red line can fit the whole data; however, when faulty operations caused by poor control of RTUs are considered in the area 1, the actual predicted line could be the black one because RCU energy consumptions in the area 1 are too low caused by undefined stage operations. In contrast, RCU energy consumptions in the area 2 seem to be outliers if the outliers are identified by typical methods based on energy consumptions without interaction consideration; with the interaction, the data are normal because high OAT and ZAT.

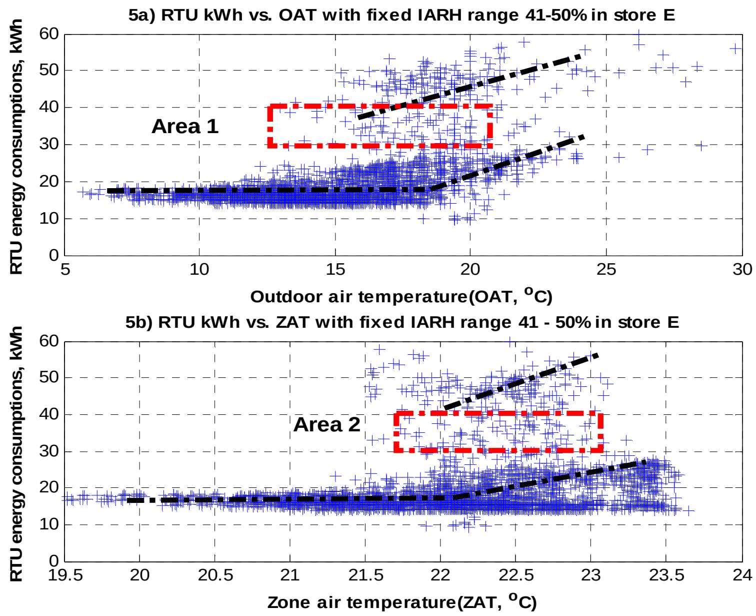

Figure 7. Faulty operations of the RTUs in store E

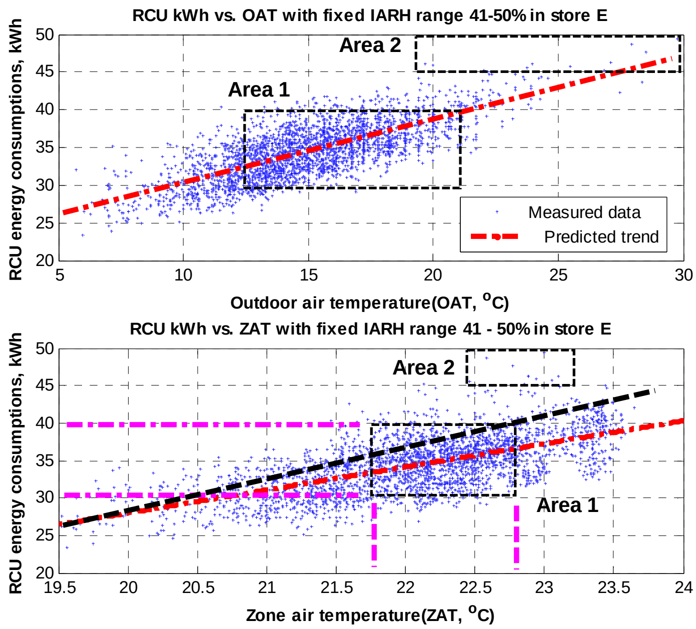

Figure 8. Poor HVAC control operations effect on RCU operations

5. Conclusion

Even through prior research papers and commercial reports have been intensively analyzed for energy savings and energy interaction effect based on IARH values, no previous study investigates the effect of faulty HVAC operations influencing on RCU energy consumptions and full HVAC&R procedure analysis as an easy-to-use tool. Moreover, faulty interaction is not considered to enhance robustness of

FDD methods on refrigeration systems. This article proposes the improved energy interaction based on the systematical 3 procedures. The first step is a preliminary process to combine all available information. After selecting the machine, the second step is to firstly evaluate control performance of RTUs in each store. In the ended process, occurred outliers in the analysis can be identified the cause whether they are from different set-points or poor control performance. To isolate faulty conditions of the RTUs, the improved energy signature is applied to reduce IARH effect to RCU energy consumptions by separating the IARH ranges in 20-30% RH, 31-40% RH and 51 – 60 %RH. Then, RCU energy consumptions versus OAT and ZAT can be usefully plotted to notice the RCU operations by considering corresponding faulty interactions provided by HVAC systems. The results show that the improved interaction can isolate outliers caused by faulty energy interaction, not caused by the RCU operations.

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References
[1] D. Woradechjumroen H. Li, Y. Yu. Energy Interaction among HVAC and supermarket environment. International Journal of Civil, Architectural, Structural and Construction Engineering 8 (12) 2014 1119-1126.
[2] P.J. Adams, J.R. Paul. The intereffect of supermarket refrigeration and air conditioning. ASHRAE Transactions 91 1985 423-433.
[3] ASHARE, ASHRAE Handbook – Refrigeration, ASHARE, 2014.
[4] H. Henderson. Data summary--[Wal-Mart] neighborhood markets. CDH Energy Report, January 2001.
[5] H. Henderson. Power use trends for Wal-Mart neighborhood stores. CDH Energy Report, December 1999.
[6] R. Farmarzi, R. Sweetser, R. Henninger. Investigation of relative humidity impacts on the performance and energy use of refrigerated display cases, Final Report GRI-00/0084. 2000.
[7] C. Laverrenz. Effective [effect of] in-store humidities on system design. Tyler Memo.1987.
[8] C. Laverrenz. Display case loads and in-store hudimities. Tyler Sales Engineering Bulletin SE-7-84. 1984
[9] S.M. Van der Sluis. Review of calculation programs for supermarket DX refrigeration systems year-round energy consumption. IIR/IIF D1-subcommission “Refrigerated Display Cabinets” Glasgow (UK) Meeting, August 31st, 2004.
[10] Y.T. Ge, S.A. Tassou. Performance evaluation and optimal design of supermarket refrigeration systems with supermarket model “SuperSim”. Part II: Model applications. International Journal of Refrigeration 34(2) 2011 540-549
[11] A. Wichman, J.E. Braun. Fault detection and diagnostics for commercial coolers and freezers. HVAC&R Research 15(1) 2009 77-99
[12] H. Henderson, M. Khattar. Measured impacts of humidity level on defrost performance and refrigerating system energy use. ASHRAE Transactions 109(1) 1999.
[13] D. Kosar, O. Dumitrescu. Humidity effects on supermarket refrigerated case energy performance: A database review – Part 1. ASHRAE Transactions 111 2005 1051 – 1060.
[14] M.J. Brandemuehl, P. Cole. Balancing latent heat Load between display cases and store comfort cooling final report for ASHRAE Project No. 1467-RP, 2013
[15] J. K. Kissock, J.S. Haberl, D.E. Claridge. Development of a Toolkit for Calculating Linear, Change-Point Linear and Multiple-Linear Inverse Building Energy Analysis Models for ASHRAE Project No. RP-1050, 2004.
[16] California Public Utilities Commission. Evaluation Measurement and Verification of the California Public Utilities Commission HVAC High Impact Measures and Specialized Commercial Contract Group Programs 2006-2008 Program Year Final Consultant Report Submitted: February 10, 2010 Volume 1