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Smart Building Solutions for Investigating Humidity Impact in Supermarkets

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Abstract

A few supermarkets have been tested for indoor humidity level impacting on refrigeration system energy use because there are cost-prohibitive and time-consuming in terms of long-term data collections so as to quantify the effect of store humidity to refrigeration power consumptions. To overcome these issues, this article collects related physical data from building automation system (BAS) of six supermarkets located in different regions in U.S. through web-based protocol communication, which is one of the sub-systems utilized for data carriers in smart building solutions. The paper applies systematical and easy-to-use procedures of energy interaction analysis and multiple linear regressions (MLR) for investigating and analyzing equipment operations and energy interaction. Due the collected data obtained from the field tests, their equipment probably includes faulty operations. Therefore, the operation investigations of improper heating, ventilation and air-conditioning (HVAC) and refrigeration systems are processed through energy interaction analysis. Following this procedure, the operations are separated into three cases: normal, faulty and acceptable conditions. In case of the acceptable and normal conditions, MLR is utilized to predict the power consumption of refrigeration systems based on the three independent variables including: an outdoor air temperature (OAT), zone air temperature (ZAT) and indoor air relative humidity (IARH). With the model prediction, MLR is also applied to separate out the effect of OAT from refrigeration power consumption so as to evaluate the impact of IARH on refrigeration systems. Decoupling OAT from IARH via MLR, energy savings can be obtained when IARH is reduced from 55% to 30%. The procedures of this analysis can be utilized as a tool and guide to routine operations of HVAC systems in order to optimize refrigeration energy consumptions in supermarket buildings.

***Keywords**:* Energy Interaction, Multiple Linear Regression Analysis, Supermarkets, Indoor Humidity and Building Automation System

1. Introduction

Smart building solutions are perspective technologies to efficiently improve building energy systems. A BAS is one of the current solutions applied to smart building areas, and can refer to a wide range of computerized building control systems and intelligent building services through central computer stations. The building control of modern BAS utilizes four level architectures including: management level; integration level; field controller level and sensor/actuator level. Meanwhile, the building services are all building facilities consisting of heating, ventilation and air-conditioning (HVAC) systems, electrical systems, lighting systems, fire systems and security systems and life systems. To communicate and exchange information between each device and subsystem of the BAS, BACnet which is a communication protocol for building automation and control network has been developed and became ASHRAE/ANSI standard 135 in 1995. With this communication protocol, web-based energy applications can be used to connect a local BAS to automatically collect online data. As a result, this technology has been applied to install on electricity-intensive type of building applications for mainly improving overall building performance. Especially in supermarket areas [1], 50% of energy consumption is consumed by refrigeration systems, whereas 20% of the total is belonged to HVAC operations.

Normally, refrigeration systems are designed at the outdoor condition of selected location [2] and 75°F (24° C) and 55% RH for an indoor condition. Faulty indoor conditions of the refrigeration systems provide by HVAC systems may result in excessive power consumption. The suitable indoor condition of refrigeration systems can happen when the sizing and suitable operations of HVAC systems are proper. The indoor conditions of the refrigeration systems provided by HVAC systems are called "energy interaction".

The interactions between improper indoor conditions and refrigeration systems lead to excessive power consumption in supermarkets. For instance, HVAC systems provide inappropriate indoor condition in a supermarket (e.g., 60% RH and 78 °F) and then the refrigeration equipment (e.g., refrigeration compressors) can consume more energy because latent load is increased due to more IARH. Conversely, whenever IARH could be controlled between 55% and 30% RH at 75°F for a zone temperature, the power consumption of refrigeration systems can be reduced [3]. The interaction in terms of energy consumption in a supermarket environment have been significantly concerned more than two decades; the results of power reduction percentages were concluded in the database review presented by Kosar and Dumitrescu [3]; however, a few supermarkets have been tested for indoor humidity level impacting on refrigeration system energy use because there are cost-prohibitive and time-consuming in terms of long-term data collections so as to quantify the effect of store humidity to refrigeration power consumptions. To overcome this point, this paper applies web-based energy protocol in terms of field testing data platform to automatically collect data from six supermarkets located in different climate in the U.S. to potentially investigate humidity impact in supermarket power consumptions.

2. Backgrounds

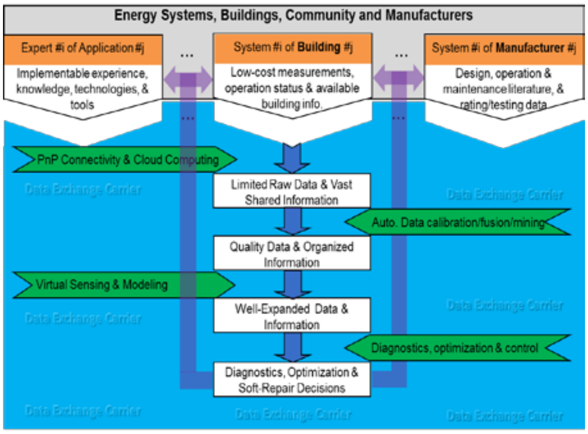

Fig. 1 Vision of smart building solutions [4]

The smart building solutions as shown in Fig. 1 enhance the multi operations and multiple connections of energy systems, building environment, community and manufacturers through data exchange carrier which performs plug-and-play (PnP) connectivity and has unlimited data memory of a could computing technology. With the final process in terms of diagnostics and soft-repair decisions for building routine operations, the building community (owners, contractors, operators, energy consultants and so on) can directly evaluate or analyze building performance through big data via web-based energy technologies. In addition, sufficient operations proved by field data can be used as tools, applicable technologies or implementable experience for educational demonstration prototypes and educational outreach program. For this research, the associated works with the smart building solutions are briefly as follows:

2.1 Data Exchange Carrier

The main functions are: 1) PnP and near-zero-cost connectivity, 2) unlimited data storage and sharing capacity, 3) unlimited computing capacity using clouding computing and 4) configuration wizards and generic tools for building performing monitoring, building diagnostics, optimal/adaptive control and reporting and service scheduling features. With increased amount of buildings/systems/users connected to this platform, the amount of shared information and the platform will be more powerful. The building community connections can reduce the cost of use in terms of unnecessary data storage, can enhance more field-proven demonstration and are more scalable for optimally managing energy efficiency in new buildings and building renovation.

Applying the data carrier to the research, the main server is connected to BACnet protocol of six supermarkets. The data related to HVAC and refrigeration systems were exported from the server in comma separated value (CSV) format. To manage this big data efficiently, Visual basic for applications (VBA) macro codes are created to sort and organize the data categories.

2.2 Data Collection Process

Data frequency depends on the available hard drive space of each BAS. In case of data limitation, the data frequency can be stored in short intervals around 1 – 5 minutes but for a limited amount time, 1 – 3 days. To keep the data longer, the sampling interval around 15 minutes is applied for longer amounts of time around 1-2 weeks. If the data are stored at short intervals for a limited amount of time, a user cannot see trends because the data will have already been replaced with new data. Additionally, if data are stored in large intervals, there can be a loss of granularity that is critical for analysis. For example, it is not uncommon for compressors to turn on and off within 10 minutes. Therefore, if a BAS were collecting data every 15 minutes, theoretically, it could miss every time the compressor turns on and off, giving the user the impression that the compressor is never activated.

For the analysis performed in this study, data were collected from each BAS at an average frequency of two minutes for the HVAC and refrigeration systems. Furthermore, the power meter data were collected at either one minute or 15 minute intervals. The data were stored on servers, with much larger capacities than a BAS, and no data were deleted from the servers. In order to reduce the amount of data to a manageable level, averages were taken from each sensor from each hour. Calculating the averages for each hour drastically decreased the time it took to perform the analysis and still maintained data integrity. Additionally, by averaging the power meter data, kilowatt hour values were obtained instead of kilowatt values.

3. Typical interaction

The supermarket refrigeration systems are designed based on the two driving conditions consisting of: 1) the indoor conditions (zone temperature and indoor RH) provided by HAVC systems and 2) outdoor air temperature. The faulty indoor conditions significantly affect the degraded efficiency and performance of refrigeration systems in supermarket leading to excessive power consumption. To investigate field data, energy interaction is a potential tool for verifying data performance obtained from sensors [5]. The typical interactions between considered parameters and equipment are explained as follows:

3.1 Rooftop Unit (RTU) versus OAT, IARH and ZAT

The interaction between a RTU and IARH is not significant because indoor relative humidity is not the controlled parameter; the RTU is controlled by set points of temperature. However, IARH may strongly affect RTU compressor power consumption indirectly in case of inherent over-sizing issue. As a result, the latent capacity is not properly absorbed leading to high IARH. Fig. 2 illustrates the latent capacity degradation model proposed by Henderson [6]. This model is fitted by the correlation between the runtime fraction (RTF) of a compressor (see RTF definition in [7]) and the ratio of sensible capacity over total capacity (SHR). It can be noticed that RTF being at 40% corresponds to SHR 1; it implies the latent load cannot be absorbed by the cooling coil of a RTU for a conditioned space because a coil is saturated. Applying this model, high IARH may be caused by the operations of oversized RTUs leading to higher power consumption in supermarkets.

Meanwhile ZAT is directly related to the set point of a temperature. The difference between this variable and the set point temperature is controlled by a RTU in the range of dead band temperature in a thermostat. Thus, it is not fluctuated if RTU operation performs normally; the expected Pearson's correlation coefficient (R) value between ZAT and RTU should be medium.

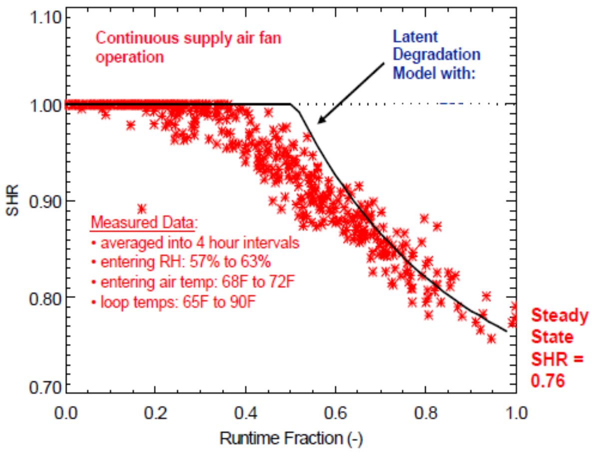

Fig. 2 Correlation between SHR and compressor runtime fraction [6]

3.2 Dehumidification Unit (DHU) Energy Consumption versus OAT, IARH and ZAT

A DHU uses desiccant wheel to absorb indoor moisture and also uses condenser unit as a heat exchanger to release heat; both IARH and OAT are driving forces of a DHU. If the DHU is activated by the set point of IARH, the R value should be at least in the medium range for this correlation because this packaged unit is required for the improvement of IARH in supermarkets; however, the correlation would be fluctuated due to the potential impact of OAT applied to reactivation section and dehumidification section in a desiccant DHU. Consequently, the correlation between OAT and the DHU can vary from low to medium value if the operation occurs in high OAT. Meanwhile ZAT is not functioned by the set point of IARH. Then, the R value should be low.

3.3 Refrigeration Compressor Energy Consumption versus OAT, IARH and ZAT

Refrigeration system also uses condenser to release heat from the refrigerant of refrigeration circuit to OAT. Thus, the correlation between OAT and refrigeration compressor energy consumption should be relatively similar to the relation between a RTU and OAT. Whenever OAT is high, the temperature of the condenser module is also high; this module of refrigeration systems will consume more energy. This correlation normally happens for a dry condensing unit on a roof. Following the application, the correlation between refrigeration compressor energy consumption and OAT is expected at least medium level because dry condensers are used for the present research.

In practice, IARH refers to latent load in a conditioned space; when IARH is higher at a constant zone temperature provided by HAVC systems, more energy consumption is occurred by the higher latent load. AT the high level of IARH, the refrigeration compressor will consume more power. Regarding this relation, the R value for this correlation should be very similar to the correlation of refrigeration compressor energy consumption versus OAT.

ZAT is the indoor condition of refrigeration systems and can be controlled by the operation of RTUs. This variable is one of the driving forces used in the sizing of refrigeration equipment. Although it is manipulated by the set point temperature of a thermostat, it is fluctuated by the variation of OAT. Thus, the R value could be in the medium range.

3.4 Anti-sweat Heater (ASH) Energy Consumption versus OAT, IARH and ZAT

An ASH is directly controlled by an IARH sensor, so the R value could reach to 1; however, the correlation probably could not be perfectly linear depending on how proper controller is operated. Normally, 55% RH is set for the on-status of an operation, whereas 25% RH is set for an off mode [8]. Using the function of a controller, the ASH is not strongly affected by OAT and ZAT because this device is typically applied to a low-temperature case to avoid the condensation on case door; it directly relates to latent load. The R value of both OAT and ZAT will be low. Therefore, if there is any significant correlation between the ASH power consumption and OAT or ZAT, the location should be in a humid environment and the DHU is not properly dehumidifying the incoming outdoor air.

The results of correlation investigation are tabulated in Table 1. The table concludes the R values between equipment power consumption and the three independent parameters.

Table. 1 Expected R values of interaction between equipment power consumption and independent parameters

Equipment	Independent parameters		
	OAT	IARH	ZAT
RTU	Medium	Low	Medium
DHU	Medium	Medium	Low
Refrigeration	Medium	Medium	Medium
ASH	Low	High	Low

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

4. Interaction Analysis

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

Supermarket	IARH Range (%)	OAT Range(°F)	ZAT Range(°F)
A	20 - 63	50 - 90	61-72
B	25 - 70	42 - 99	67-75
C	45 - 54	69 - 105	69-74
D	27 - 50	51 - 88	72-75
E	68 - 76	44 - 93	18-60
F	23 - 62	42 - 87	66-75

First of all, the analysis is processed on refrigeration systems to investigate the operational conditions of equipment by comparing calculated R values to the expected ranges of R values for the energy interactions as resulted in Table 1. In the research, α equaling to 0.05 is selected as the critical value to examine null hypothesis between uncorrelated two variables for all interactions. RTUs and refrigeration compressors located at 6 supermarkets are investigated by the interaction approach as case studies.

The R values of refrigeration compressor are given in Table 3 by computing correlations between the three independent variables (OAT, IARH and ZAT) and power consumptions. If the calculated R values are in the expected ranges of the interaction, equipment performs normally. Otherwise, they probably have developing or sudden faults in routine operations.

Based on the R-value calculations, all R values are obtained based on the computed p values that are less than the level of significance ($p < 0.05$); the null hypothesis of uncorrelation between two variables is rejected. Consequently, the three independent parameters and RTU power consumptions are significantly correlated with the level of significance ($\alpha = 0.05$). With the comparison between Table 1 and Table 3, Table 4 concludes the investigation results of refrigeration operations.

Table. 3 R values between the independent variables and the power consumption of refrigeration compressors

Supermarkets	OAT	IARH	ZAT
A	0.86	0.75	0.67
B	0.85	0.46	0.37
C	0.88	-0.44	0.78
D	0.71	0.48	0.35
E	0.93	0.67	0.56
F	0.83	0.61	0.68

Table. 4 Investigations of refrigeration operation by comparing Table 1 to Table 3

Supermarkets	OAT	IARH	ZAT
A	Normal	Normal	Normal
B	Normal	Fault	Fault
C	Normal	Fault	Normal
D	Normal	Fault	Fault
E	Normal	Normal	Normal
F	Normal	Normal	Normal

5. MLR analysis

After investigating the operations, supermarket A has the normal operations of refrigeration compressors. In this section, multiple linear regression (MLR) is used to predict the power consumption of refrigeration systems in supermarket A. With normal conditions, a computed MLR will be adjusted in order to obtain the relation between IARH and refrigeration power consumption for evaluating supermarket operations in terms of a reduction percentage.

Based on the typical MLR procedures [9], independency investigation is firstly conducted. The results in Table 5 conclude that all tolerance values ($1-R^2$) are higher than 0.1, so there are the indecency of each pair in the three independent variables. These three parameters can be used to construct a MLR if each one has strong relation on a dependent variable with significance.

Table. 5 Independency investigations between each independent variable

Tolerance	OAT	IARH	ZAT
OAT	0	0.469	0.520
IARH	0.469	0	0.839
ZAT	0.520	0.839	0

In order to examine the relation between two parameters with the significance, the level of correlation can be checked by one-way ANOVA. T-statistic values are used to examine the hypothesis of each independent variable by comparing with t-statistic values from t distribution critical values at the specific significance selected as 0.05 for the study. For supermarket A, the t-statistic value, which is obtained from the t distribution table, of the three independent variables (OAT, IARH, and ZAT) at $t_{0.975,\ 2474}$ is 0.196 being less than the t-statistic values in Table 6.

On the one hand, all p values in Table 6 are less than the significance at α=0.05. Therefore, the analysis accepts the alternative hypothesis (H_a). As a result, OAT, IARH and ZAT significantly impact on the total refrigeration power consumption and can be utilized to construct a MLR equation in next step.

Table. 6 One-way ANOVA examining the relation between the independent variables and the total power consumption of refrigeration systems

Independent variables	Coefficients	Standard error	T-statistic value	P value
Intercept on kWh axis	-38.939	2.821	-13.80	0
ZAT	0.826	0.044	18.90	0
IARH	0.255	0.006	45.22	0
OAT	0.162	0.006	27.53	0

6. Humidity Impact Analysis

After the step of systematically selecting the independent variables and examining the influence of each variable on the total refrigeration power consumption, the MLR equation can be obtained with the significance at 0.05 or within the 95% of the confidence interval. The model validation is conducted via coefficient of determination (R^2). The MLR model of refrigeration system power consumption (kWh) in supermarket A is:

$$kWh = 0.162\times OAT + 0.255\times IARH + 0.826\times ZAT - 38.939 \qquad (1)$$

In Eq. (1), the total refrigeration power consumption is influenced by OAT, IARH and ZAT at R^2 being 0.87. This value is considerably high for a baseline model to recheck fault operations of refrigeration systems in other supermarkets owned by the same brand or having the similar equipment operations. With the good accuracy of MLR, the relation between refrigeration systems and IARH can be obtained in terms of a simple linear regression (SLR) as follow:

$$kWh_{ad} = kWh - 0.162\times OAT - 0.826\times ZAT = 0.255\times IARH - 38.939 \qquad (2)$$

According to Eq. (2), the reduction percentages of power consumption obtained by the adjusted power consumption (kWh_{ad}) can be computed for the supermarket when IARH is decreased from 50 to 35%. The energy saving percentage is around 25.5 %. Meanwhile, the effect of OAT in terms of R^2 decreases from 0.74 to 0.49; the impact of ZAT also reduces from 0.49 to 0.15. Energy saving can be obtained if IARH can be controlled under 50% RH. This optimization can be conducted by optimizing the HVAC operations such as optimally adjusting the RH set point of a DHU. The relation between kWh_{ad} and IARH can be plotted in Fig. 3

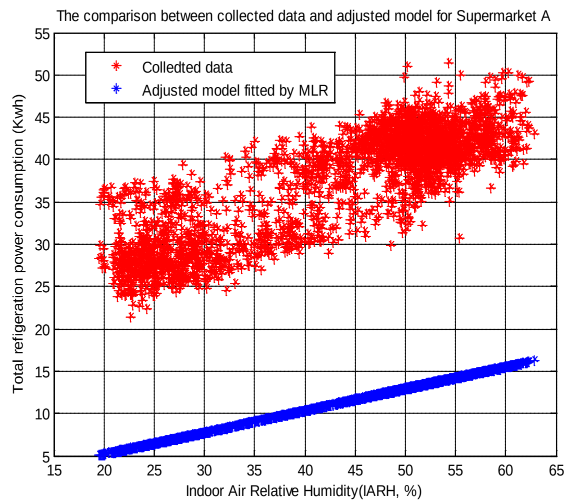

Fig. 3 The relation between adjusted power consumption versus IARH in supermarket A

Fig. 3 depicts the example applying the adjusted model to reduce the effect of OAT and ZAT from total refrigeration power consumption versus IARH in supermarket A, whereas the red points are the observed total power consumption of refrigeration systems. The comparison between the predicted values obtained the adjusted model and observed data shows that the adjusted model can be used to reduce the effect of other parameters to the total refrigeration power consumption. The range of kWh is between 5 and 16 approximately that are affected by IARH because the R^2 value is almost 1 based on SLR analysis.

7. Conclusion

This study reduces time-consuming and cost-prohibitive issues for obtaining field test data by applying smart building solution concept via BACnet protocol. The methodology is developed for investigating equipment operations through power consumption and measured variables without using fault-free data since, in a field test, common faults are gradually developing in routine operations due to improper commissioning, installations and preventive maintenances. Consequently, fault-free cannot be directly obtained from supermarket buildings.

To be more specific, Pearson's correlation coefficient of typical interactions among HVAC and supermarket environment are evaluated based on theoretically normal operations of each equipment through the three measurements including OAT, IARH and ZAT. By using recommended R values in abnormal, acceptable and normal ranges, the three measurements are used as independent variables, whereas equipment power consumptions are dependent parameters. The examined R values of field test data with the level of significance at 0.05 are compared to the expected R values of each normal interaction. After the comparisons, simple faulty interactions can be identified when the investigated R values are out of the lower bound of the expected ranges. The operational condition of each machine will result in the overall performance of equipment in terms of increased power consumption.

The operational condition of each machine will result in the prediction performance of power consumption obtained by MLR equation. To systematically obtain MLR, the independency between each independent variable (OAT, IARH and ZAT) is firstly examined by the tolerance method. With the results, OAT, IARH and ZAT are applicably independent. Following the procedures of MLR, one-way ANOVA is utilized to analyze the impact of the independent variables on the total refrigeration power consumption.

The results show that OAT, IARH and ZAT are the independent variables that strongly affect the power consumption of refrigeration systems with significance. With normal operations of typical interactions, MLR is used to well fit the total refrigeration power consumption by using OAT, IARH and ZAT (R-square > 0.70). To further evaluate IARH influence on refrigeration power consumption, the adjusted model in terms of SLR is utilized to decouple OAT impact from the total power consumption of the refrigeration systems. The well fit of the adjusted model will have a high R-square value. The proposed procedures are applied to the building example, supermarket A. The finding is that the total refrigeration power consumption can be optimized when IARH can be reduced from 55% to 30% by any technique such as the soft repair approach for mitigating oversizing impact. Moreover, the accurate MLR can be used as a baseline model for FDD application in supermarket buildings having similar equipment with the similar routine operations.

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