Fault Detection Involving Unfavorable Interaction Effects to Enhance the Fault Diagnostics of Refrigeration Systems in Commercial Supermarkets

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List of Symbols

EST = energy signature temperature (°C)

IARH = indoor relative air humidity (%)

OAT = outdoor air temperature (°C)

p value = probability measure (dimensionless)

r value = Pearson’s correlation (dimensionless)

ZAT = zonal air temperature (°C)

Greek symbols

α = level of significance

List of abbreviations

ASH = anti-sweat heater

ASHRAE = American Society of Heating Refrigerating and Air-Conditioning Engineers

BAS = building automation system

DHU= dehumidification unit

F = faulty operations

FDD = fault detection and diagnosis

GUI = graphical user interface

HVAC = heating, ventilation and air conditioning

HVAC&R = heating, ventilation, air conditioning and refrigeration

MBCx = monitoring-based commissioning

N = normal operations

PAU = packaged air-conditioning units

RCU = refrigeration compressor rack unit

RMS = remote monitoring system

RTU = rooftop unit

SLR = simple linear regression

Abstract

Most HVAC&R machine issues are inherently caused by problems in routine operations, decommissioning problems, improper design, and poor installation, and these issues can result in excessive energy consumption and a short equipment lifespan.

Existing fault detection and diagnosis (FDD) methods for refrigeration systems have been considered in supermarket environments. However, typical HVAC systems are generally operated without considering indoor conditions as the drivers of refrigeration operations. This issue leads to unreliable refrigeration data for FDD design.

This article systematically proposes a novel fault detection method for faulty HVAC operations related to problems in routine operations and the excessive energy use of refrigeration systems. Four steps are developed as a novel unfavorable interaction strategy to identify abnormal HVAC operations based on identified energy signatures. Outdoor and zonal air temperatures (OAT and ZAT) are concurrently utilized to specify typical area operations for rooftop units (RTUs). A fault detection approach is proposed based on RTU outliers using plots of OAT and ZAT versus the energy consumption of the refrigeration system based on fixed 10% differences in the indoor relative humidity range. The findings of a case study involving five supermarkets demonstrate the potential to identify the outliers that cause unsuitable dead-band zones and temperature set points for RTU operations, which can lead to excessive energy consumption of refrigeration units. The proposed methodology enhances the data reliability and robustness of FDD for refrigeration systems.

Keywords: Building Automation System; Energy Interaction; Fault Detection and Diagnosis; Unfavorable Interaction; Remote Monitoring System

1. Introduction

Supermarkets are characterized by high energy consumption and are complex integrated systems in commercial buildings. Specifically, refrigeration equipment consumes 7% of the total energy in this sector [1]. In each supermarket, 40-50% of the total energy is consumed by refrigeration machines. Moreover, coupled heating, ventilation and air conditioning (HVAC) systems account for 20-35% of total consumption [2]. Display cases are operated to maintain indoor case temperature for goods quality while display case cooling load is changed regarding ambient conditions provided by HVAC systems. If the operating conditions deviate from the typical design conditions (e.g., 24 ºC with 55% RH) of the HVAC systems, the situation can cause a load increase for refrigeration systems when other related conditions are constant, such as the product load and electrical load. Moreover, selecting the wrong refrigeration equipment in a renovated building can cause control problems with the conditions of the zonal environment. Non-ideal indoor conditions can lead to excessive power consumption in the HVAC and refrigeration systems. Such relations are called "Energy interactions" [3] or "intereffects" [4].

With these complex systems, there are several challenges to obtaining energy savings and achieving CO_2 reduction by analyzing optimal solutions of the energy interactions [5 - 6]. For example, simulation-based monitoring systems have been continuously applied in compressor rack supermarket systems to estimate energy savings [7 - 11]. However, several factors were not considered in the developed models because unexpected zonal conditions and situations can occur in real applications. Thus, field test data were collected for energy audits and energy analysis based on simplified techniques such as the energy signature approach [12]. Additionally, the energy savings of refrigeration equipment have been determined based on the indoor humidity ratio considering interactions [7, 13 - 16]. The results indicated that maintaining an indoor relative humidity lower than 40% can save energy for refrigeration systems, and this issue is not cost-effective for air conditioning systems during the summer [17]. To ensure the satisfactory performance of machines in supermarkets, systems can be enhanced by utilizing monitoring-based commissioning (MBCx) [18] techniques, which can avoid problems associated with improper design, unsuitable installations and poor routine operations.

In terms of commercialization, commercial monitoring systems have been continuously developed by multiple brands [19] for given building automation systems (BASs) and remote monitoring systems (RMSs). Such systems can be applied to establish set points and fault alarm functions for HVAC and refrigeration systems. Sensors are used to link routine operations with a graphical user interface (GUI). BAS and RMS features are useful and convenient for the user operation of HVACR systems. However, most of these centralized monitoring systems are cost-prohibitive to install in practice, especially in developing countries. As a result, a fault detection and diagnosis (FDD) method for monitoring the system interactions among HVAC and refrigeration units cannot be developed in practice because the data types of the two systems are not synchronous; therefore, additional sensors are required and must be linked to one of the two systems.

Recently, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) research project RP-1615 [20] summarized a strategy for developing full FDD techniques for supermarket equipment. Rule-based fault characteristics of a rooftop unit (RTU) and data driven based on power consumption data were applied in simple fault diagnosis for a compressor rack refrigeration system [20]. To increase limitations of data in the project, Behfar and Yuill [21] extended simulation results for fault-free and faulty data of a commercial refrigeration system with effects of liquid line receivers using grey-box models. One of the findings revealed that a steady-state modeling approach is required to reduce the complication and fluctuation of large refrigeration systems. The project stated that several sensors are not appropriate for monitoring the interactions between HVAC and refrigeration systems. From the survey of service record [22], unfavorable interaction from faulty HVAC operations were not the four most costly faults (refrigerant charge, compressor, oil and condenser fans, respectively) to repair. In addition, the operation of real supermarkets involves a large number of uncontrolled conditions, which can lead to unsatisfactory data quality and inaccurate thresholds for superheating and subcooling temperatures. These factors may be affected by unfavorable interaction information provided by HVAC systems. For example, non-design zone conditions such as too high zone temperature or humidity level leads to increase cooling load of display cases; indoor temperature of the display cases will be higher resulting in higher power consumption of refrigeration compressor rack unit (RCU). To further study the effects of energy use interactions in supermarkets, Ding et al. [11] developed a retail store model that was validated with operational data within a 10% error band for electricity use. Beyond energy use prediction, rule-based root cause analysis was conducted for RTU control and stage cooling mismatch analysis. OA dampers were further investigated based on a statistical learning-based root cause method. However, the RTU faults that affect refrigeration systems have not yet been considered. Similar to previous research, Wit et al. [23] developed the EnergyPlus model for investigating the interactions between HVAC and refrigeration systems because routine HVAC operations are difficult to constrain in practice. The zonal temperatures and supply temperatures of refrigerated cases were varied to study energy use variations. However, BAS and RMS are seldom synchronized based on the same data platform. Thus, the pattern analysis results of the simulation could be limited in real-world implementation. Mylona et al. [10] also developed an EnergyPlus model that was calibrated with real operational data from the UK for studying the interdependence of different factors, including HVAC&R systems, lighting systems, store operations and occupancy patterns. This simulation model can accurately predict energy use in supermarkets, and the results can be used in interaction analyses involving subsystems and supermarket envelopes to increase the energy savings potential. The study found that the highest energy savings was 4% when the HVAC systems were operated only during store hours. Mavromatidis et al. [24] developed a supermarket model-based ANN for the FDD model training process. Viable data were used for multiple ANN processes, such as data cleaning and data quality control, due to black-box performance limitations. Some interactions, such as humidity variations and rule-based routine operations, were not considered in the calibration processes. Widsonkun at al. [25] studied interaction effect for control performance between four packaged air-conditioning units (PAU) in an open space; the interaction resulted in wrong control operations of PAUs and oversizing [26, 27]. Moreover, detailed analysis of the interactions between air-flow distribution and air-conditioning supply diffuser types are essentially recognized for infection prevention and control, especially in operating rooms and hospital environments [28]. Although at least five prior studies investigated unexpected system occurrences due to system interactions, additional data collection and monitoring are necessary. Additionally, real-time implementations could require expert or well-trained analysts and researchers. Rule-based and approach-based systematic analyses and data analysis are useful and can reduce the initial cost of installation. Moreover, fault effects are not considered in models of refrigeration system energy interactions.

Considering low-cost monitoring systems and FDD implementations in field tests in developing countries, Srinivasan et al. [29] applied the SARIMA model to predict energy consumption with cause-effect analysis in retail store operations. Woradechjumroen [30] and Woradechjumroen and Tongshoob [31] reviewed and simulated non- invasive monitoring systems for HVAC&R operations in supermarkets. Although prior research has recognized the importance of the interactions among supermarket energy systems, these studies mainly considered energy savings features and analyses based on the normal operation of HVAC systems. FDD methods have been implemented for HVAC and refrigeration systems, but the system interactions have not been considered in field tests. Without using the well-controlled operating conditions provided by HVAC systems, improper indoor relative humidity (IARH) levels and ZATs can cause deviations and fluctuations in refrigeration system operations. These significant issues can lead to fault detection problems and result in low data quality for FDD analysis. To enhance the FDD analysis process for supermarkets in practice, this article systematically proposes a novel fault detection scheme that considers system interactions, user-friendly statistics and a novel rule-based method for diagnosing faulty indoor driving force conditions caused by poor controllers or variations in routine operations. The findings provide a new procedure to: 1) reduce the outliers caused by the effects of the unfavorable interaction of HVAC operations on RCU operations, and 2) isolate unfavorable interaction effects from the overall operation of refrigeration systems. Isolating the cause of the poor control and faulty operations of an HVAC system can enhance the FDD approach for refrigeration. The paper is systematically organized as follows. First, the related background and limitations of only considering simple energy interactions are discussed. Then, the new method is proposed in steps. Finally, the method is applied to identify the unfavorable interaction effects in refrigeration systems, and in energy saving applications.

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References

1. U.S .DOE (2011) Office of Energy Efficiency and Renewable Energy. In: Buildings Energy 2010.
2. Tassou SA, Ge YT. (2008) Reduction of refrigeration energy consumption and environment impacts in food retailing. In: Handbook of Water and Energy Management in Food Processing, Woodhead Publishing Series in Food Science, Technology and Nutrition, Cambridge.
3. Woradechjumroen D, Li H, Yu Y (2014) Energy interaction among HVAC and supermarket environment. International Journal of Civil, Architectural, Structural and Construction Engineering 8 (12): 1119-1126.
4. Adams PJ, Paul JR. (1985) The intereffect of supermarket refrigeration and air conditioning. ASHRAE Transactions 91:423-433.
5. Barbieri N, Palma A (2017) Mapping energy-efficient technological advances in home appliances. Energy Efficiency 10(3): 693–716
6. Filina-Dawidowicz L, Filin S (2018) Innovative energy-saving technology in refrigerated containers transportation. Energy Efficiency. https://doi.org/10.1007/s12053-018-9729-2
7. Bahman A, Rosario L, Rahman MM (2012) Analysis of energy savings in a supermarket refrigeration/HVAC system. Applied Energy 98: 11-21.
8. Tassou SA, Ge YT (2011) Performance evaluation and optimal design of supermarket refrigeration systems with supermarket model "SuperSim" Part I: model description and validation. International Journal of Refrigeration 34: 527 – 539.
9. Brandemuehl M.J, Cole P (2013) Balancing latent heat Load between display cases and store comfort cooling. ASHRAE Project, No. 1467-RP, Final report.
10. Mylona Z, Kolokotroni M, Tassou SA (2017) Frozen food retail: Measuring and modeling energy use and space environment systems in an operational supermarket. Energy and Building 144: 129 – 143.
11. Dong B, Gorbounov M, Yuan S, Wu T et al (2013) Integrated energy performance modeling for a retail store building. Building Simulation 6: 283 – 295.

12. Kissock JK, Haberl JS, Claridge DE (2004) Development of a toolkit for calculating linear, change-point linear and multiple-linear inverse building energy analysis models. ASHRAE Project, No. RP-1050, Final report.
13. Woradechjumroen D, Li H, Promwattanapakdee T (2015) Smart building solutions for investigating humidity impact in supermarkets. Paper presented at ICOME 2015 Conference, Petchburi, Thailand, December 16-18.
14. Henderson H, Khattar M (1999) Measured impacts of humidity level on defrost performance and refrigerating system energy use. ASHRAE Transactions 109 (1): 1051 - 1060.
15. Howell RH, Adams P (1991) Effects of indoor space conditions on refrigerated display case performance. ASHRAE Project, No. 596-RP, Final report.
16. Kosar D, Dumitrescu O (2005) Humidity effects on supermarket refrigerated case energy performance: a database review – part 1. ASHRAE Transactions 111: 1051 – 1060.
17. Orphelin M, Marchio D, Bech, S (1997) Significant parameters for energy consumption in frozen food area of large supermarkets. Paper presented at CLIMA 2000 Conference, Brussels, Belgium, August 30 - September 2.
18. Wang L, Greenberg S, Fiegel J, Rubalcava A et al (2013) Monitoring-based HVAC commissioning of an existing office building for energy efficiency. Applied Energy 102: 1382–1390.
19. Behfar A, Yuill D, Yuebin Y (2017) Automated fault detection and diagnosis methods for supermarket equipment (RP-1615). Science and Technology for the Built Environment 23 (8): 1253 – 1266.
20. Behfar A, Yuill D, Yuebin Y (2019) Automated fault detection and diagnosis for supermarkets–method selection, replication, and applicability. Energy and Buildings 198: 520–527.
21. Behfar A, Yuill D (2020) Numerical simulation of fault characteristics for refrigeration systems with liquid line receivers. International Journal of Refrigeration 119: 11- 23.
22. Behfar A, Yuill D, Yuebin Y (2018) Supermarket system characteristics and operating faults (RP-1615). Science and Technology for the Built Environment 24(10): 1104-1113.
23. Witt H, Taylor S, Lomas K, Liddiard R (2015) Simulation of energy use in use in UK supermarkets using Energyplus. Paper presented at IBPSA 2015 Conference, Hyderabad, India, December 7-9.
24. Mavromatidis G, Achab S, Shahb N (2013) Diagnostic tools of energy performance for supermarkets using Artificial Neural Network algorithms. Energy and Buildings 62: 304–314.
25. Widsonkun W, Woradechjumroen D, Vongbunyong S (2019) Interaction analysis investigations of multiple supply duct split-type air-conditioning units in an open space. IOP Conf. Ser.: Mater. Sci. Eng. 501: 012052.
26. Woradechjumroen D, Yu Y, Li H, Yang H, Yu D (2014) Analysis of HVAC system oversizing in commercial buildings through field measurements, Energy and Building 69: 131-143.
27. Woradechjumroen D, Li H, Yu Y (2016) Soft-repair technique for solving inherent oversizing effect on multiple RTUs. Building Environment 108: 47 – 62.
28. Baracat TM, da Silva CA, Lofrano FC, Kurokawa FA (2020) Assessment of the performance of airflow in an operating rooms using ceiling supply and sidewall inlet systems. Journal of the Brazilian Society of Mechanical Sciences and Engineering 42(41).
29. Srinivasan S, Vasan A, Sarangan V, Sivasubramaniam A (2015) Bugs in the freezer: detecting faults in supermarket refrigeration systems using energy signals. Paper presented at ACM e-Energy 2015 Conference, Bangalore, India, July 14-17.
30. Woradechjumroen D (2016) Smart building energy solutions technologies – possible implementations and limitations in Thailand supermarkets. Paper presented at ICOME 2016 Conference, Chiang Mai, Thailand, December 13-16.
31. Woradechjumroen D, Tongshoob T (2017) Data fusion technique for leveraging reliability of supermarket field data. Paper presented at ICOME 2017, Bangkok, Thailand, December 12-15.