

บทคัดย่อ

รหัสโครงการ: MRG5980208

ชื่อโครงการ: การพัฒนาและการประเมินวิธีการตรวจจับและวิเคราะห์ความผิดพลาดของระบบปรับอากาศและความเย็นที่ใช้ในซูเปอร์มาเก็ตเชิงพาณิชย์

ชื่อนักวิจัย และสถาบัน ดร. เด่นชัย วรเดชจำเริญ มหาวิทยาลัยศรีปทุม

อีเมล: denchai.wo@spu.ac.th

ระยะเวลาโครงการ: 2 ปี

บทคัดย่อ: ระบบปรับอากาศและความเย็นส่วนใหญ่เสื่อมประสิทธิภาพลงตามระยะเวลาเนื่องมาจากปัญหาความไม่เหมาะสมจากการเดินเครื่องประจำวัน, การปรับการทำงานเครื่อง, การออกแบบและการติดตั้ง ก่อให้เกิดการสิ้นเปลืองพลังงานและอายุการใช้งานที่สั้นลงของอุปกรณ์ การแก้ปัญหาดังกล่าวนำไปสู่ศักยภาพการลดพลังงานระหว่าง 15 ถึง 30 เปอร์เซ็นต์ การแก้ไขและปรับปรุงระบบในอาคารเก่าสามารถประหยัดได้ถึง 30 เปอร์เซ็นต์ ระบบวินิจฉัยแบบอัตโนมัติสามารถลดปัญหาความผิดพลาดและค่าบำรุงรักษาในระบบที่ซับซ้อน โดยระบบอัตโนมัตินี้สามารถควบคุมกระบวนการเดินเครื่องอย่างเหมาะสมได้อย่างต่อเนื่องนำไปสู่ระบบพลังงานที่มีประสิทธิภาพด้วยความอัจฉริยะ จากประโยชน์ข้างต้นทำให้ระบบวินิจฉัยแบบอัตโนมัติได้เป็นที่สนใจและมีงานวิจัยเกิดขึ้นอย่างแพร่หลายมากกว่า 20 ปี หากแต่ยังขาดเครื่องมือที่มีประสิทธิภาพและราคาเหมาะสมมาช่วยในการออกแบบระบบวินิจฉัยที่สามารถแยกความผิดพลาดที่เกิดพร้อมกันได้โดยเฉพาะระบบพลังงานแบบรวมศูนย์ของทั้งอาคารดังเช่นระบบซูเปอร์มาเก็ต

รายงานฉบับนี้นำเสนอขั้นตอนระบบวินิจฉัยแบบใหม่สำหรับระบบการทำความเย็นแบบรวมศูนย์ประกอบด้วย 1) ขั้นตอนการวิเคราะห์ผลกระทบความผิดปกติของปฏิสัมพันธ์ต่อระบบทำความเย็น 2) ขั้นตอนการปรับปรุงคุณภาพข้อมูลที่ได้จากการวัดภาคสนาม 3) ตัวคัดกรองข้อมูลที่สถานะคงที่แบบใหม่โดยใช้ข้อมูลการใช้งานตู้แช่สินค้าและ 4) การนำกฎการแยกคุณสมบัติความผิดพลาดมาประยุกต์ใช้กับระบบความเย็นแบบรวมศูนย์ โดยวิเคราะห์ความเป็นไปได้และข้อจำกัด ผลการศึกษาพบว่าทั้ง 4 ขั้นตอนสามารถนำไปปรับปรุงคุณภาพของข้อมูล และนำไปวินิจฉัยความผิดพลาดอย่าง ความสกปรกของคอนเดนเซอร์และอีวาพอเรเตอร์, การกลับตัวไม่หมดของแก๊สที่คอนเดนเซอร์และ การรั่วซึมของลิ้นวาล์วคอมเพรสเซอร์โดยปราศจาก การปรับปรุงและรบกวนการทำงานของระบบความเย็นดั้งเดิม

คำหลัก : การตรวจจับและวินิจฉัยอัตโนมัติ; ความผิดปกติของปฏิสัมพันธ์; ระบบตรวจสอบจากระยะไกล ; ระบบปรับอากาศและความเย็น; ตัวคัดกรองที่สถานะคงที่

Abstract

Project Code: MRG5980208

Project Title: Development and assessment of fault detection and diagnosis methods for HVAC&R in commercial supermarkets

Investigator: Dr. Denchai Woradechjumroen Sripatum University

E-mail Address: dENCHAI.WO@SPU.AC.TH

Project Period: 2 years

Abstract: Most degraded heating, ventilation, air-conditioning and refrigeration (HVAC&R) machines are inherently caused by problems in routine operations, non-commissioning, improper design, and installations; these issues result in excessive energy consumptions and a shorter equipment life cycle. Energy savings potential on average ranges from 15 to 30 % and many field retrofit investigations demonstrated up to 50% of energy savings. To minimize faults and costly maintenance in an integrated complex system, automated fault detection and diagnostic (AFDD) can automate the process of continuous commissioning and endow the building energy systems with intelligence. With the benefits brought by AFDD, several researches have been conducted for HVAC&R systems during the past two decades. However, they still lack of potential tools to design efficient AFDD approach for distinguishing simultaneous faults with cost-effectiveness on an integrated energy system in supermarkets. This report proposes the novel FDD strategy for a centralized compressor-rack refrigeration system consisting of: 1) fault detection analysis of faulty interaction effect on refrigeration operations; 2) a data cleaning procedure to improve data quality of HVAC&R operations; 3) a novel steady-state detector based on refrigerated display case operations; and 4) decoupling-based features applied in the compressor-rack refrigeration system in terms of possibility and limitations. The results show that the procedures can be used to mitigate faulty data including in collected field data, and to diagnose the typical faults (evaporator and condenser fouling, non-condensable and compressor valve leakage) without system operation intervention.

Keywords: Automated fault detection and diagnosis; Faulty interaction; Remote monitoring system; HVAC&R; Steady-state detector

Executive summary

Supermarkets are the most electricity-intensive types in commercial buildings in which the operations of heating, ventilation and air-condition and refrigeration (HVAC&R) systems are coupled in terms of energy interaction; However, the status quo of these system operations is, non-personalizable with low energy efficiency, high operation and maintenance expenditure, and high environmental impacts. Energy savings potential on average ranges from 15 to 30 % caused the faults by or non-optimal operations. Automated fault detection and diagnostic (AFDD) can automate the process of continuous commissioning and endow the building energy systems with intelligence so that they can self-diagnose problems and even self-execute correcting actions for non-optimal operations or provide recommendation reports for building operators or service contractors to fix the problems promptly and optimally schedule preventative maintenances.

With growing realization of the benefits brought by AFDD, a lot of research on AFDD for HVAC&R systems has been conducted during the past two decades. However, AFDD has not been implemented on proven field performance of integrated whole-building energy systems for supermarkets HVAC&R because potential tools and design information are not sufficient for designing efficient AFDD approach with cost-effectiveness and non-intrusive system.

This report proposes novel systematical procedures of a FDD method for a compressor-rack refrigeration system. At first, proposed metrics are developed to review and synthesize related documents, simulation, control systems, previous AFDD projects. Procedures of developed FDD and monitoring systems are then evaluated via the metrics before installations and implementations. The finalized procedures consist of four components: 1) fault detection analysis of faulty interaction effect on refrigeration operations; 2) a data cleaning procedure to improve data quality of HVAC&R operations; 3) a novel steady-state detector based on rule-based typical refrigerated display case operations; and 4) decoupling-based feature for FDD is investigated on a compressor-rack refrigeration system in terms of reliable diagnostics, limitation, and performance uncertainties.

Fault detection analysis of faulty HVAC operations for problems in routine operations and excessive energy of refrigeration systems. Four steps are developed as a novel interaction strategy to firstly identify abnormal HVAC operations based on an identified energy signature point. Outdoor and zone air temperature (OAT and ZAT) are concurrently utilized to specify typical area operations of rooftop units (RTU). A fault detection approach is proposed with the outliers of RTUs by using plots of OAT and ZAT versus refrigeration energy consumptions based on fixed 10% differences of an indoor relative humidity range. The findings of the case study from five supermarkets show potential detections to identify the outliers caused unsuitable dead-band temperature and zone set points of RTU operations which lead to excessive energy consumptions of refrigeration units.

A data cleaning technique is developed to improve data reliability for effective HVAC&R performance analysis. The technique is composed of the three stages. At first, the data are analyzed based the control functions of HVAC&R systems and driving force condition ranges (zone temperature, indoor relative humidity and outdoor temperature). Then, outlier identification based on z-scores (standard scores) is used to determine outliers from a normal power consumption. Thirdly, when an outlier is detected, the energy interaction ranges at the period of the identified abnormal variation are rechecked, and fixed indoor relative humidity ranges are also used to reduce the effect to refrigeration systems. The technique can be further used as one of the procedures to clean abnormal data conditions for fault detection and diagnosis (FDD) process.

A steady-state detector is essential to isolate transient response or unsteady state performance to obtain suitable steady state operations. Especially, the centralized refrigeration system used for supplying refrigerant to multiple display cases is operated under several uncontrolled factor or improper commissioning and set-point setting, beyond customer uses and product loading periods. Typical thresholds based detailed system operations are designed to test real data obtained from web-based user interface of the refrigeration system. The results show the novelty of the steady-state detector can perform well, and be further used for satisfying the objective for FDD design and obtaining steady-state data.

Based on the evaluated monitoring system design and aforementioned three procedures, FDD can be efficiently for diagnosing refrigeration system operations without fault-free data. Decoupling-based feature applied in rooftop units and chillers are improved to propose a novel FDD approach called a novel strategy based decoupling feature for FDD on a commercial centralized refrigeration system. The algorithm is adjusted from the system operation information of experienced contractors in Thailand. With the design parameter interaction based on the approximated same load operations of two fault levels and fault-free data of chiller vapor compression cycle in ASHRAE RP-1043, the proposed novel technique can diagnose the typical faults (evaporator and condenser fouling, non-condensable and compressor valve leakage) on the compressor-rack refrigeration system based on non-invasive approach using the existing measurement of the commercial controller. The procedures of this report can be further applied in testing of Thai supermarkets for quantifying robustness and sensitivity before implementing as real-time and embedded systems on a commercial web-based controller of each supermarket in the future.

1. Objectives

This research fund is mainly proposed to develop an applied research methodology for smart preventative maintenances and the enhancement of machine productivity by diagnosing faults inherently occurring in air-conditioning and refrigeration systems in Thailand commercial supermarkets. The objectives of this current project are:

To collect and evaluate significant information that includes: 1) Studying typical faults occurring in both HVAC (air-conditioning units) and refrigeration systems (centralized refrigeration system) and system operation characteristics; these characteristics include: a) the typical equipment and systems in a commercial supermarket, including the sequence of operations that describe how the components and systems are controlled and interacted; 2) studying and measuring interaction characteristics between HVAC and refrigeration systems because refrigeration systems are typically operated based on the environment provided by HVAC systems; and 3) measuring and verifying Static and dynamic operation data based on fault-free and faulty conditions of HVAC&R from two Thailand supermarkets.

To evaluate, improve and enhance simplified transient model of supermarket system from previous projects.

To develop real-time monitoring systems for measuring: 1) indoor interactions between air-conditioning and refrigeration systems; 2) related system operations of the air-conditioning system; and 3) more thermodynamic parameters beyond existing parameters of the on-board controller in centralized refrigeration system.

To review and evaluate existing fault detection and diagnosis (FDD) approaches from other HVAC&R applications.

To select potential FDD approaches such as decoupling based feature, simple linear regression (SLR), multiple linear regression (MLR) and principal component analysis (PCA) for diagnosing faults in the supermarket system (centralized refrigeration system and supply air-conditioning units with indoor condition interaction), excluded lighting systems and self-contained refrigeration units.

2. Methods

2.1.1 AFDD tool design and essential document analysis

Successful cases of real-time FDD implementations in field tests are firstly studied as cases studies. For chiller system, the achieved projects are ASHRAE RP1043, RP 1275, and RP1486 which they were conducted to achieve: 1) essential tools, fault-free data and faulty-lab data; 2) evaluation of offline AFDD method with the data of ASHRAE RP1043; and 3) AFDD method implementation called decoupling-based feature (DBF).

2.1.2 Commercial HVAC&R controllers

They are studied to identify significant parameters for evaluating system performance including: on-off pressure control of a rooftop refrigeration condenser; multiple stage operations of the compressor; thermal expansion valve used to control compressor-rack refrigerant; zone interaction

2.1.3 Monitoring systems based literature review

Typical faults considered from item 2.1.1 are synthesized for considering essential parameters to design a well-monitored platform.

2.1.4 Existing system and data evaluation

- Establishing metrics or KPI to collect to quantify the benefits of AFDD.
- Testing the metrics against case studies, specifically projects that are Non-AFDD versus AFDD in the same organization in order to minimize variables.
- Evaluating the resultant information from the case studies and simulations.
- Providing conclusions from the data.
- Validating the proposed framework model established to evaluate the advantages and limitations of AFDD. The process is depicted in Fig. 1.

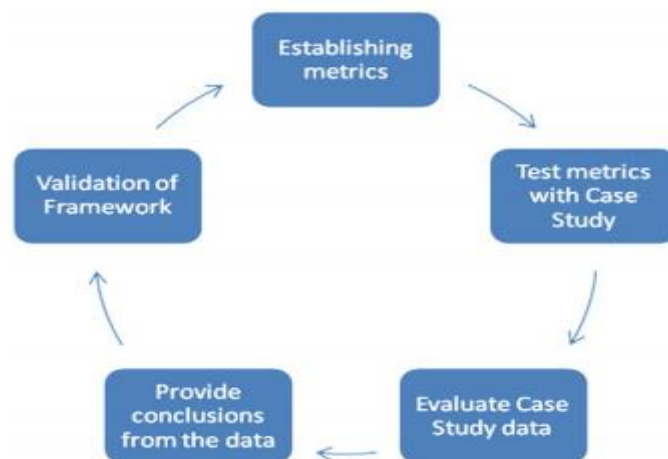


Fig. 1 Framework of AFDD design [1]

2.2 Fault detection analysis of energy interaction effect for HVAC&R operations

Step 1: Information collection in analysis

General HVAC&R operations are composed of store schedules: data of driving force conditions, mechanical systems, and control sequences and energy consumptions from sub-meters. In this step, since the OAT and ZAT sensors are both embedded into each RTU controller linked to a BAS server, they can be remotely downloaded from anywhere.

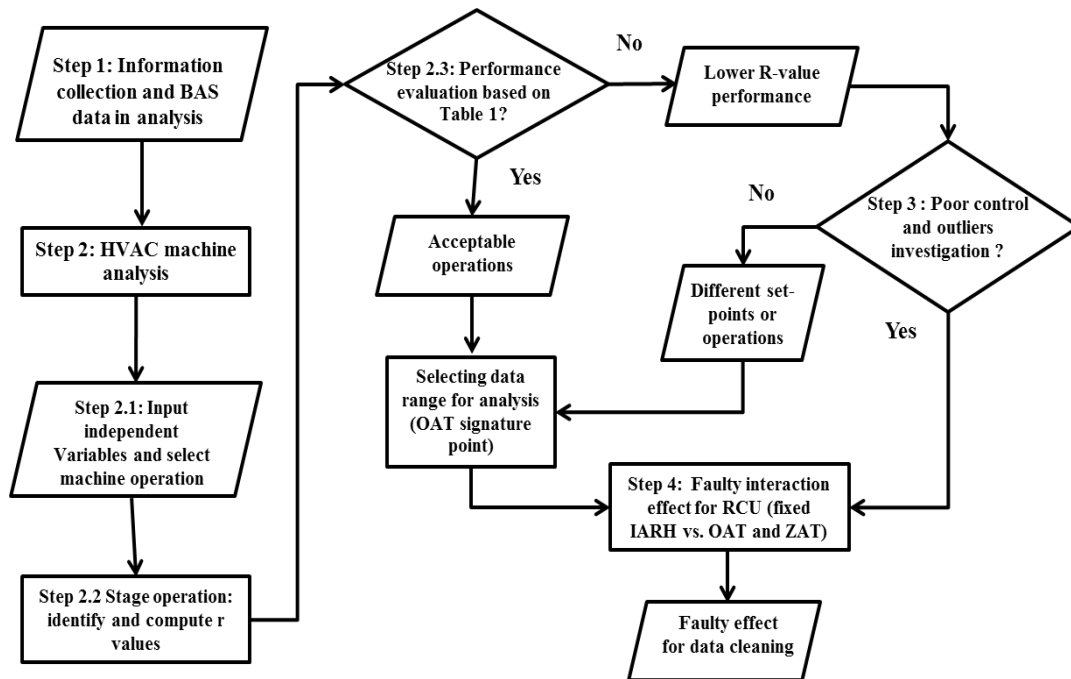


Fig. 2 Improved energy interaction method with rule-based performance identifications

Step 2: HVAC machine analysis

For HVAC analysis to mainly identify machine controller performances the improved interactions are depicted in Fig.2 and the procedures are as follows:

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

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

Step 2.3 is to compare the computed value from Step 2.2 to the expected values in Table 1. This stage operation identification can improve r value performance.

Table 1 Expected r values between HVAC&R energy consumptions and the parameters [2]

The r value of the interaction between power consumption and parameters	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

Step 3: Outlier identification

Outliers are lower r values than the expected range in Table 1. Set points are useful to assure that outliers or scattered data are caused by different set points in different periods (occupied and unoccupied periods), not from faulty operations such as poor controllers. At this step, different operational periods are used to further investigate faulty operations of HVAC systems.

Step 4: Faulty operation effects on RCU

To enhance the analysis, several IARH ranges are fixed within 10 % RH such as 30-40% and 40-50%. Then, the two OAT areas (OAT > EST and OAT < EST) are used as an independent variable of RCU energy consumptions to plot SLR, in which each SLR line is based on the fixed 10% RH range.

2.3 Data cleaning technique for improving data quality of zone interaction

From data sorting of the obtained CSV files in last section, six steps depicted in Fig. 3 are designed as follows: Step 1 is to compute an average value ($\bar{x}$) and standard deviation (sd) of equipment kWh; the control equipment is staged on when OAT is more than 60 °F in each store for further quantifying abnormal kWh in terms of outliers.

Step 2 is further used to compute z-score in Eq. (1).
$$z = \frac{x_i - \bar{x}}{sd} \quad (1)$$

, where $x_i = kWh_i$ of each machine at an identified sampling time

Step 3 is to identify outliers when computed z is more than the selected value, $z > 2$ or $z < -2$ (95% confidence); if not, the process goes back to step 1 for rechecking the statistical values and re-selecting a new threshold.

Step 4 is utilized to reduce data errors by deleting outliers from the original data since most of excessive power consumptions in terms of the outliers are caused by faulty operations.

Step 5 is the verification process by examining that the identified periods of outliers are not influenced by severe OAT changes because high OAT may result in high power consumptions. The

interaction between OAT and kWh is conducted for the verification by using consistent IARH difference range (e.g. 30-40%)

Step 6 is to improve data quality; three fixed IARH ranges are used to isolate IARH effect from refrigeration power consumption. With the specific data range, OAT versus kWh is assumed to be linear relation to examine equipment operations based on the control functions.

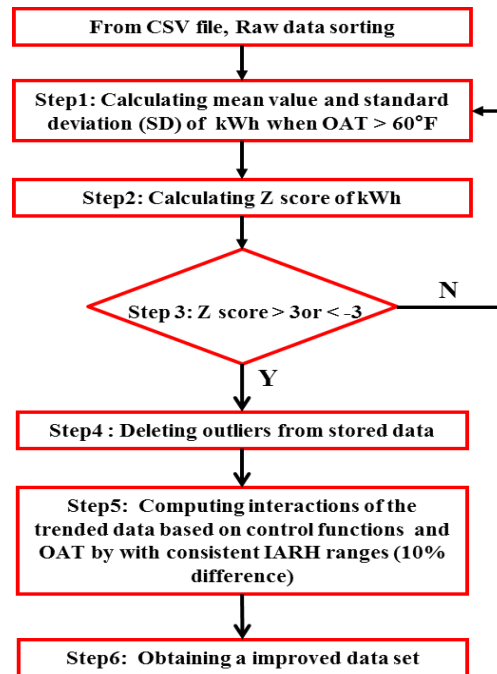


Fig. 3 Outlier Identification Procedure

2.4 Steady-state design based typical display case operations

This section provides a simple data fusion technique to improve the data quality for obtaining reliable data operations. For the analysis example, TXV position curve is used to calibrate the normal operations because valve section oversizing is a problematic to suitable refrigerant control based superheat temperature (Tsh) operations for well-conditioned display cases. Baseline equipment and control sequences and routine operations of commercial supermarket systems were surveyed and studied. Especially, thermostatic expansion valve (TXV) is directly used to control amount of refrigerant flow for suitable temperatures in display cases; faulty or inappropriate sizing of this equipment leads to typical faults such as compressor valve leakage and refrigerant overcharge. The wrong valve sizing selection also causes excessive power consumptions in compressor rack operations. Unsuitable operations can be used to enhance the steady-state detector design. To this end for the analysis, TXV position curve in Fig. 4 is used to calibrate the normal operations because valve section oversizing is a problematic to suitable refrigerant control based Tsh operations for well-conditioned display cases. However, based on the survey of Thai contractors, most of them lack of experience in setting Tsh for proper refrigerant control leading to majority problem in compressor

break down inherently. Without calibrating the unsuitable operations, FDD approaches cannot be designed effectively in case of the obtained data integrated with faulty commissioning of the TXV valve operations.

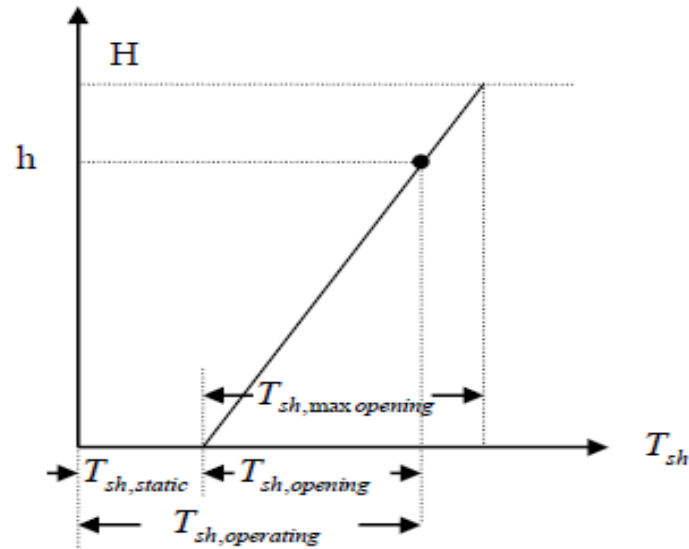


Fig. 4 TXV position curve between T_{sh} vs. h (valve position)

2.5 FDD design based on applied DBF method for a compressor-rack refrigeration system

With the field implementations and manufacturers' data survey [3], typical faults (F) cause refrigeration performance degradation called "degradation faults". They are categorized as follows:

F1: Evaporator fouling is a reduction in airflow rate that would be occurred due to ice buildup deposits on the evaporator coil. Computed airflow rate can be used to decouple this fault.

F2: Similar to F1, fouling can be developed when the condensing coil air-side becomes dirty reducing the airflow over the coil and decreasing the coefficient of performance (COP).

F3: Refrigerant undercharge is one of service faults leading to lower heat transfer efficiency. The simple trouble shooting can be simply noticed if the differences between sub-cooling temperature (T_{sc}) and T_{sh} are less than zero ($T_{sc} - T_{sh} < 0$) when the compressor load increases

F4: Refrigerant overcharge is caused by service resulting in high pressure and higher compressor work. The diagnostic condition is opposite to F3 when the same difference temperatures are more than zero ($T_{sc} - T_{sh} > 0$) when the compressor load increases. However, the fault severity level cannot be specified.

F5: Liquid-line restriction tends to accumulate during operations because a vapor-compression system can experience clogging of the filter dryer, which restricts the flow and increases pressure drop leading to a reduced mass flow rate. Temperature drop across the filter dryer is used to identify F5. However, the filter dryer was practically uninstalled after three-month commissioning of the system. Thus, F5 is not considered.

F6: Compressor valve leakage allows high-pressure refrigerant to flow back to the low side pressure causing lower the mass flow rate. Discharge Temperature (T_{dis}) can be used to diagnose F6. However, T_{dis} is not available in the controller because suction pressure (P_{suc}) is practically used to control the compressor-rack sequence control while the condenser pressure used for the on-off control of the condenser fan. Rule-based related parameters are used to notice this fault.

Beyond the Ref [3], non-condensable gas (F7) is typically occurred in the refrigerant circuit when T_{sc} is not properly selected causing non-condensed gas to liquid condition in the condenser. This happening results in higher pressure in the condenser and power consumptions of the compressor. Based on the decoupling based feature [4], condenser saturation temperature (T_{cond}) is used as the fault feature for diagnosing the fault.

2.6 Zone interaction modeling for refrigeration systems

Due to high energy consumptions of commercial supermarket operations, mathematical models have been increasingly developing to virtually study energy performance for quantifying feasible energy savings after achieving commissioning or system retrofitting. Sophisticated supermarkets have been developed for aforementioned objectives. However, based on scalable, flexible and effective software, only three significant research models were developed for supermarkets in which air conditioning and refrigeration system were modeled in terms of zone interaction. In addition, the models can be adjustable for different objectives in case of model calibration for energy savings evaluation, fault-free model and so on.

For complete retail store simulation in Fig. 5, this model simulation was conducted based on the three main modules: RTU module which was applied as Excel spreadsheet to generate indoor data conditions (air flow rate, supply temperature and humidity) supplied the zone module.

The zone module was designed based on simplified heat balance equations based on the well-mixed zone assumption; mixed humidity and temperature were sent based iteratively to the RTU module and the refrigeration display case module located in the zone.

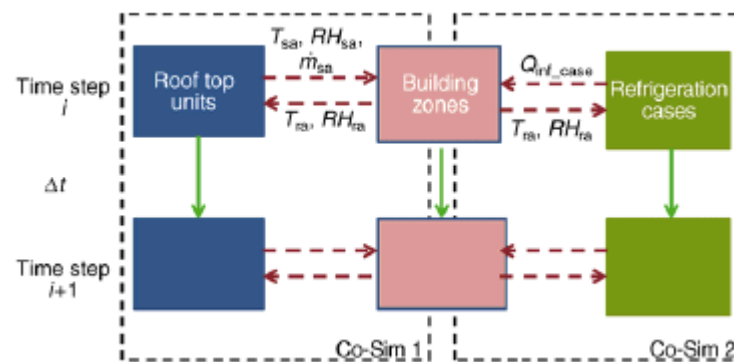


Fig. 5 Retail store simulation [5]

Using the input generated from the zone module as zone interaction conditions, heat transfer from the air curtain in display cases as infiltration load can be computed iteratively from energy balance equations within each display case. In each time step for air-side calculation, refrigerant-side conditions related to the air-side model were concurrently estimated in compressor module based standard polynomial equations and condenser using simplified dry-coil heat exchanger equation.

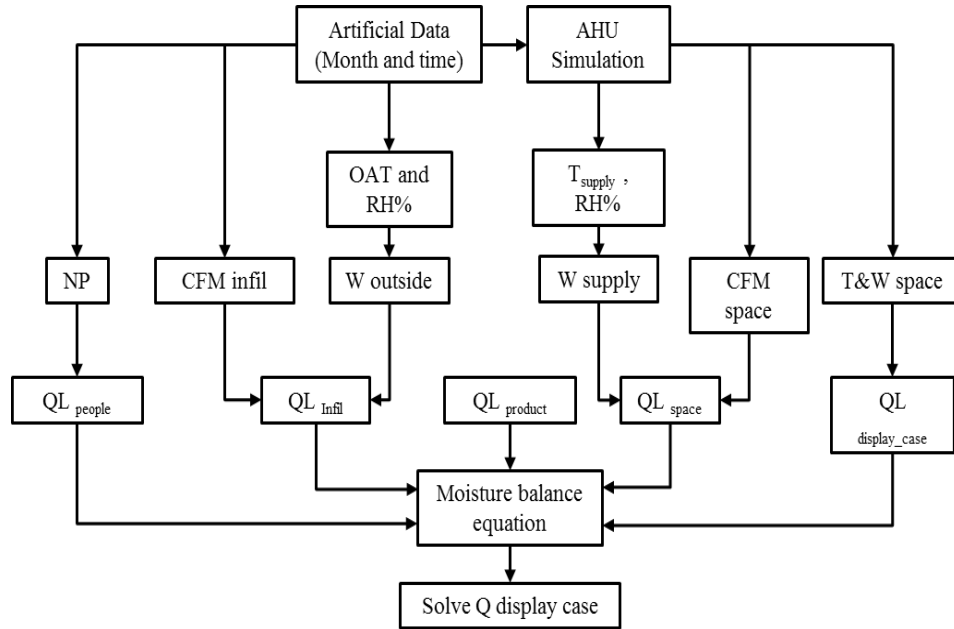


Fig. 6 Simplified Moisture balance interaction modeling [6]

The third research in Fig. 6 assumed constant supply temperature and humidity to generate indoor humidity level. Using moisture balance equation, polynomial-based display cases can be simply used to compute the heat balance of air curtain through the zone humidity condition. With the others associated heat components being assumed, the computed indoor humidity was quite close to the measured values. This research is well-suitable to study faulty interactions which typically incur in routine operations of supermarket HVAC&R systems.

3. Results

3.1.1 AFDD literature review

There are several prior studies relating to the current research; however, there is no study to systematically develop and collect suitable and potential tools to further evaluate FDD approaches in supermarkets. In terms of methodologies, even though decouple based feature has been done to isolate simultaneous faults, there is no FDD method applied to whole-integrated supermarket system. The significant researches associated with FDD for supermarket or vapor compression cycles are shown as follows:

Table 2 summarizes the prior studies of FDD associated with HVAC&R equipment used in supermarkets. In USA, RTUs are typically used to provide both cooling and heating for maintaining thermal comfort in supermarket conditioned spaces. Even though RTUs are not practically applied in Thailand or ASEAN countries, the baseline refrigerant circuit is based on vapor compression cycle that is also similar to chiller system and split-type air-conditioning units in grocery stores. However, for hyper market or supermarket like Tesco Lotus, AHUs are practically used to retain optimal indoor conditions of a supermarket. The FDD review on AHUs can be studied more in [7], so FDD on AHU is also included to consider in the current proposal.

First of all, Breuker and Braun [8 - 10] feasibly studied FDD base on advanced statistical approach and concluded typical faults in RTU operations. However, the approaches cannot diagnose simultaneous faults. As a result, Li and Braun [11 - 15] proposed decoupling-based feature to potentially isolate simulations faults based on six typical faults including: condenser fouling, evaporator fouling, compressor valve leakage, liquid-line restriction, refrigerant undercharge and refrigerant overcharge. Also, this method enhances productivity and reduces maintenance costs by 70% of yearly preventative maintenance.

For FDD for Refrigeration systems, Taylor et al. [16], Talor and Corne [17], Ren et al. [18] and Fisera and Stluka [19] conducted several techniques for FDD on refrigeration systems; however, no study concludes optimal approach for distinguishing simultaneous faults and whole-integrated multiplexed refrigeration system. Unlike the aforementioned studies, Wichamn and Braun [3] successfully conducted FDD for the lab evaluation of a cooler and freezer (self-contained unit) to isolate simultaneous faults by utilizing decoupling based feature; however, this research is under well controlled room, so energy interaction is not considered.

To detect and diagnose refrigerant circuit, a successful approach to real-time refrigerant piping operations of a distributed commercial refrigeration system was installed in a Colorado supermarket. The approach, called refrigerant leakage detection and diagnosis (RLDD), was developed and implemented by Assawamartbunlue and Brandemuehl [20]. However, this approach is not tested for simultaneous faults effect. Meanwhile, Li and Braun [4] and Wichman and Braun [3] conducted FDD on refrigerant overcharge and undercharge; however, the method was only tested on the short refrigerant circuit of packaged air-conditioning units and self-contained units, respectively.

To analyze the performance of display cases, Yang et al. [21, 22] applied Kalman filter and unknown input based observer approaches to conduct FDD on display cases without integrating with condenser and compressor rack. To fully implement FDD, the whole refrigeration system and supermarket energy interaction should be integrated because these integrated systems possibly cause simultaneous multiple-complex faults during field evaluation of the display cases.

With the aforementioned conclusion, no study applied FDD approaches for whole-integrated supermarket systems. There is no conclusion to optimally select FDD approaches to decouple simultaneous for multiplexed refrigeration systems and AHUs in supermarkets. The decoupling based feature has been only tested for RTUs and self-contained units (cooler and freezer). Also, FDD for supermarkets lacks of rich data and potential documents for designing and analyzing FDD approaches, and lacks of dynamic model of a whole-integrated supermarket model to generate fault-free and fault simulation data.

Table 2: Previous FDD approaches for HVAC&R for supermarket analysis

Supermarket equipment	Previous fault detection and diagnosis (FDD)
Rooftop unit (RTU)	Breuker and Braun [8 - 10], Li and Braun [11 - 15]
Air-handling unit (AHU)	Norford et al.[25], Schein et al.[12] and Li [26]
Refrigeration systems and commercial coolers and freezers	Taylor et al. [16], Taylor and Corne [17], Ren et al. [18], Fisera and Stluka [19], and Wichman and Braun [3]
Leakage or undercharge piping systems and refrigerant overcharge	Li and Braun [4], Wichman and Braun [3], and Assawamartbunlue and Brandemuehl [20]
Display case	Yang et al. [21, 22]

3.1.2 Commercial HVAC&R controllers

In Fig.7, it illustrates the measurement innovation for Thai service companies how useful the web-based interface controllers are beyond remote monitoring advantage for checking user operating performance. The most benefit of this modern controller is to remotely access available sensors from display cases and compressor racks (Fig. 7b) in terms of a noninvasive solution (without system intervention) via web-based user interface provided by a manufacturer (Fig. 7a). All online interfaced Subsystem controllers are shown on the website (Fig. 7c). This website can be utilized to download stored data, but not real-time data storage. However, it is suitable for FDD algorithm development in terms of offline predicted preventive maintenance. In addition, rich data of these controller installations can be used to further develop efficient big data for model calibration for evaluating the overall performance of future re-commissioning and system retrofitting. For sub-systems, a rooftop condenser is controlled by on-off control based on cut-in and cut-off pressure set points. Compressor-rack is functioned based on sequential stage on-off control. Meanwhile, each display

case is controlled the temperature using electrical expansion valve, which is more accurate than a typical TVX.

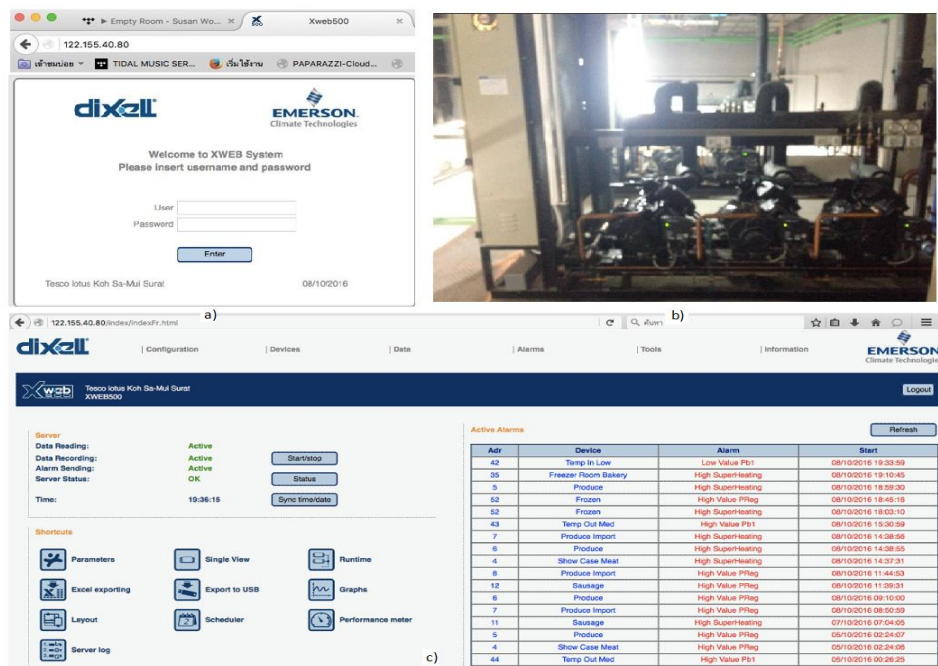


Fig. 7 Commercial web-interface monitoring

3.1.3 Monitoring system design based on existing data

The research methodology of MRG-5980208 can be mainly categorized into three main works including: zone interaction, a HVAC system (air-handling units, AHUs) and compressor rack refrigeration system. The monitoring systems of each sub-system are analyzed and modified to obtain more significant and sufficient variables for FDD approach. With the feasible investigations of existing available data obtained, the existing parameters are insufficient for FDD analysis.



Fig.8 Thai supermarket layout

Monitoring system improvement in Zone Interaction

From Fig. 8, additional monitoring systems are installed to measure the interaction between AHUs and refrigeration systems including HVAC&R machine power consumptions. The zone interaction measurement includes the zone air temperature (ZAT) and indoor air relative humidity (IARH) sensors of AHUs (point 4 and 5) and two conditioned spaces at point 1 (medium-temperature display cases) and 2 (low-temperature display cases). Meanwhile, outdoor relative humidity (RH) and outdoor temperature (OAT) are also measured as the outdoor condition used for the interaction analysis.

Monitoring system improvement in refrigeration systems

According to Fig. 9, the simplified centralized refrigeration system is composed of the identified measurement; this compressor rack system located in a control room is used to provide refrigerant to display cases in the zone interaction. The centralized refrigerant system includes: the existing monitoring system in the control panel; multi-compressor racks; outdoor condenser unit; liquid receiver; suction manifold; and refrigerant piping system. The indoor temperature of each display case will be controlled via the thermal expansion valve (TXV) which controls the refrigerant flow rate of a refrigerant circuit supplied from the control room.

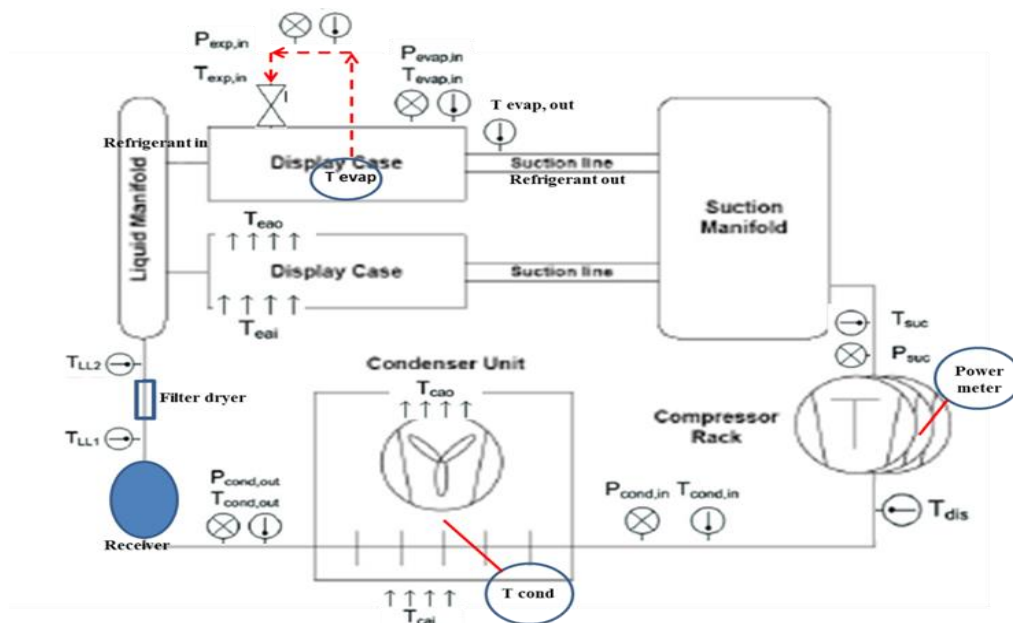


Fig. 9 simplified compressor rack refrigeration system used in a hypermarket for the research

For modified measurement system via non-invasive solution, the existing commercial monitoring system based web service interface was installed by contractor which can be downloaded via web-based user interface (WUI); however, some parameters such as P and T sensors of the refrigerant-side at the identified positions in Fig. 9 are not provided on the WUI. Fortunately, they are available embedded on the control unit for efficiently manipulate the system performance. To this end, the web service can be used to write out these parameters without additional sensors in the refrigerant

cycle. Except the outside unit, the condenser refrigerant or water temperature of an inlet and outlet are additionally installed depending on for efficient FDD development and analysis.

Monitoring system improvement in Air-conditioning System

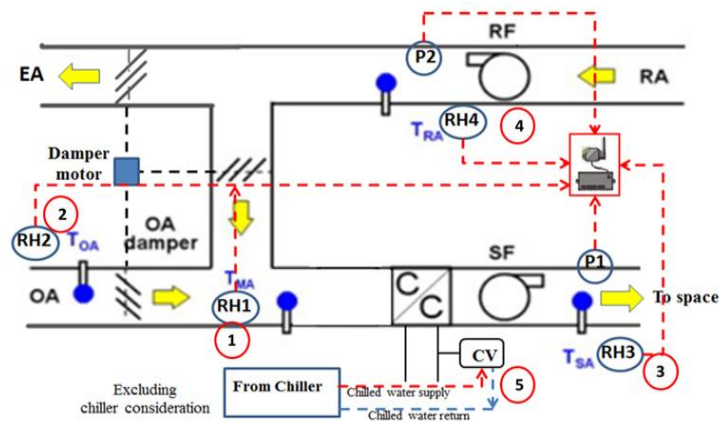


Fig. 10 A typical variable air volume AHU system

In Fig. 10, the typical VAV AHU composes of: 1) supply (SF) and return fan (RF) with constant air-flow rate; 2) fixed exhaust air (EA), outdoor air (OA) and return air damper (RA); 3) solenoid cooling vale (CV) to control zone temperature; and 4) additional monitoring system unit for measuring pressure (P), RH and T at OA, RA, mixing air (MA) area and supply air. These mentioned values are sufficient to effectively develop FDD on AHUs [7].

3.1.4 Existing data evaluation via zone interaction modeling

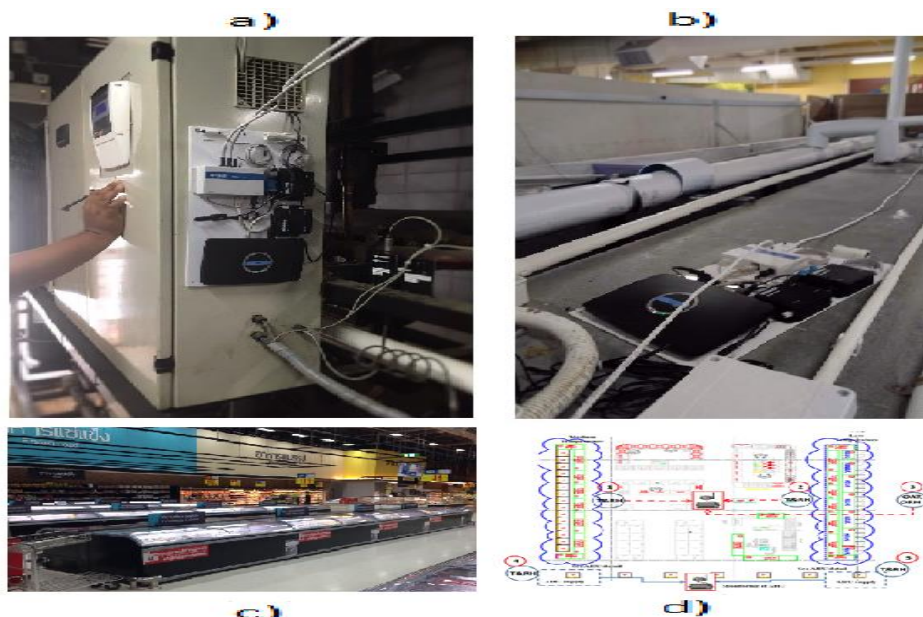


Fig.11 Hardware installation

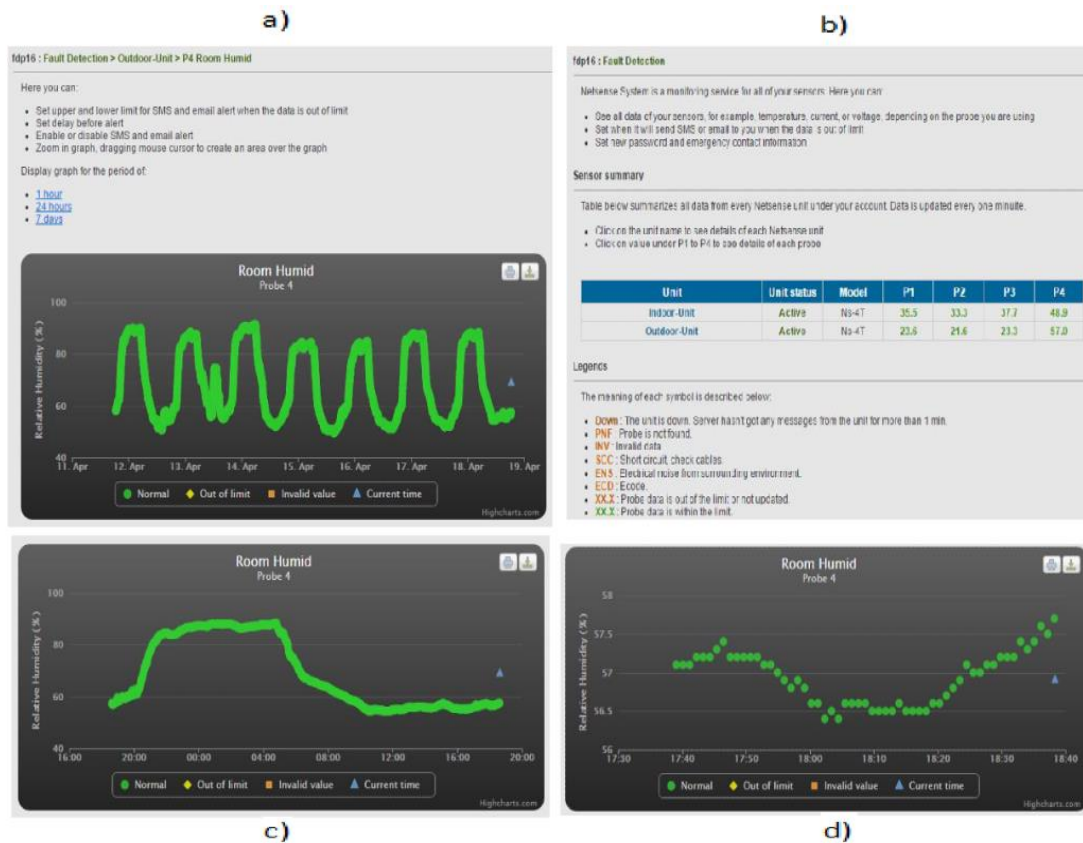


Fig. 12 Real-time interaction monitoring

In Fig.11, beyond the availability of refrigeration data performance, the physical sensors of zone interaction monitoring system between air-conditioning and refrigeration systems (Fig. 11c and 11d) is design and installed on the medium- and low-temperature display case (Fig. 11b). The sensors are sent data back to the main router installed on main control panel of the system (Fig. 11a). All indoor and outdoor humidity and temperature values are online collected via web-based graphical user interface (GUI) in Fig. 12b which is designed to identify the data periods in 7 days, 24 hours and hour period (Fig. 12a, 12c and 12d, respectively).

The simulations of mathematical models have been increasingly developing to virtually study energy performance for quantifying feasible energy savings after achieving commissioning or system retrofitting in heating, ventilation, air-conditioning and refrigeration systems. However, for mainly achieving energy savings and analysis based on scalable, flexible and effective software in supermarkets, most of the previous models were not mainly developed for studying faulty operations to leverage FDD on refrigeration system operations. This report firstly improves the existing model used for studying the potential of energy savings for humidity impact in the U.S. The model is improved by using the integration of TRNSYS and Matlab function. A simplified equation is applied in the supermarket environment for balancing latent load interaction between HVAC and refrigeration. With the agreement between the obtained data and the simulated results, the model is further used

to generate the possibly fault-free zone interaction in Thai supermarkets using the embedded outdoor data of Thailand in TRNSYS, and can be further utilized to generate fault-free data based on an improvement of the display case models.

```

1  % solve_Qdisplay_space.m
2  function w=Qdisplay_space (total2,CFMinfl,CFMspace,~,w_supply,w_outside)
3
4  %%% load data from minite sampling
5  %s stands for single display case
6  %m stands for multi decks display case
7  %c stands for closed door display case
8  %inlet air curtain temperature in K
9  Tin_s=275.15;
10 Tin_m=273.15;
11 Tin_c=268.75;
12 %difference of display case temperature - inlet air curtain temperature
13 deltaT_s=2.4;
14 deltaT_m=3;
15 deltaT_c=2.4;
16 % air curtain mass flow rate (ma=ro*v*A) where A = width*thickness
17 ma_s=1.2*0.5588*0.1016;
18 ma_m=1.2*1.325*0.114;
19 ma_c=1.2*0.675*0.0613;
20 %correlation's constants for heat transfer across the air curtain
21 c1=-0.180;
22 c2=303.180;
23 c3=-0.781;
24 c4=216.309;
25 c5=-0.448;
26 c6=509.975;

```

Fig. 13 m-file for solving heat balance for display cases in Matlab

According to the measured data obtained from the monitoring system in the first supermarket, they are very helpful to compare to the simulated data in the simulation. This simulation will further used to extend the evaluation of the proposed method in the first journal. For this project, the simulation method is improved based on the method and results in Ref [6] embedded into TRNSYS. With the simulation improvement, the m-file function (Fig. 13) is adjusted for using with TRNSYS which can be potentially used to construct fault-free conditions for interactions in typical supermarkets.

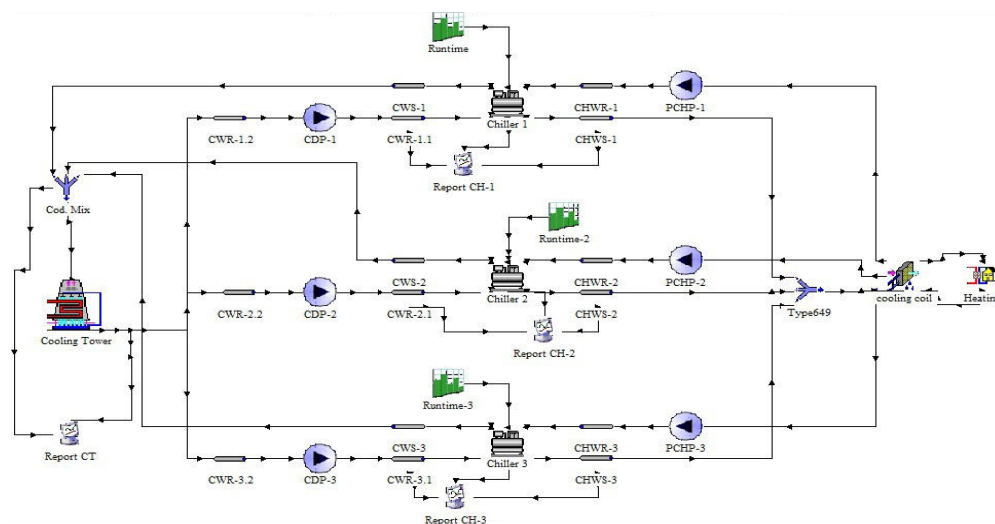


Fig. 14 Water-side chiller system in TRNSYS

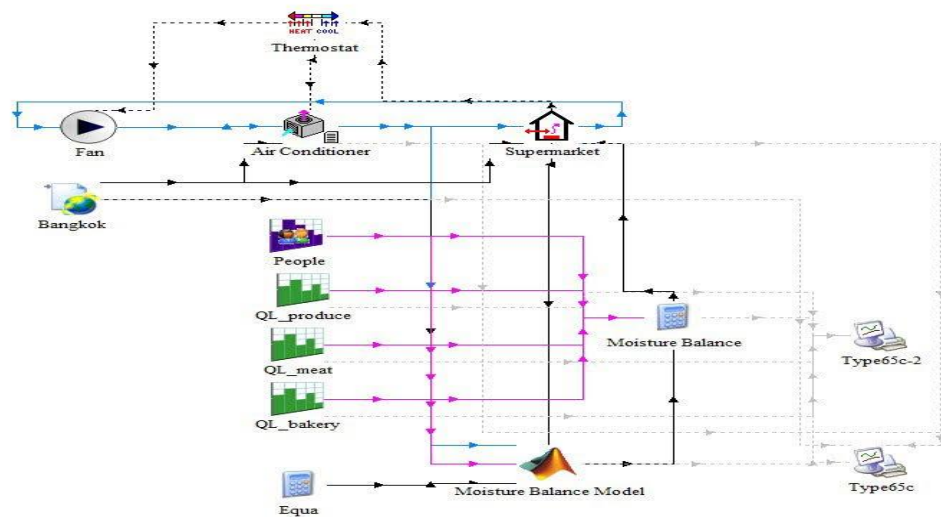


Fig. 15 Interaction system in TRNSYS

In Fig. 13, the system simulation is developed on TRNSYS for water-side chiller systems including: One cooling tower and three chiller operations. Two of them are used together to run at peak load condition while another one is used to switch the sequence of the chiller operations at peak load. The system is used to provide in hypermarket. The obtained results will be validated and calibrated via EEC Academy because the chiller system is operated via Lotus engineers who did not provide the system data of the building automation system (BAS) to the research. To reduce this limitation, another BAS data is used to confirm the verified simulation; the model can be used to generate chiller data and then will be calibrated via available of zone interaction and refrigeration system operations [23].

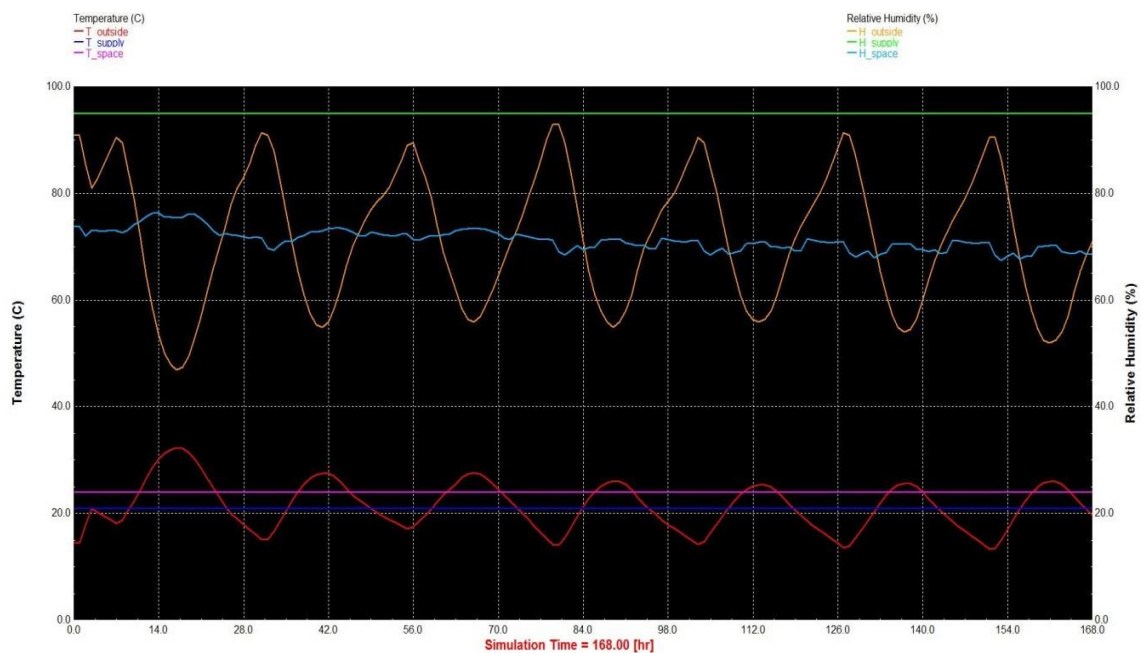


Fig. 16 Simulated interaction system data using Thailand weather in TRNSYS

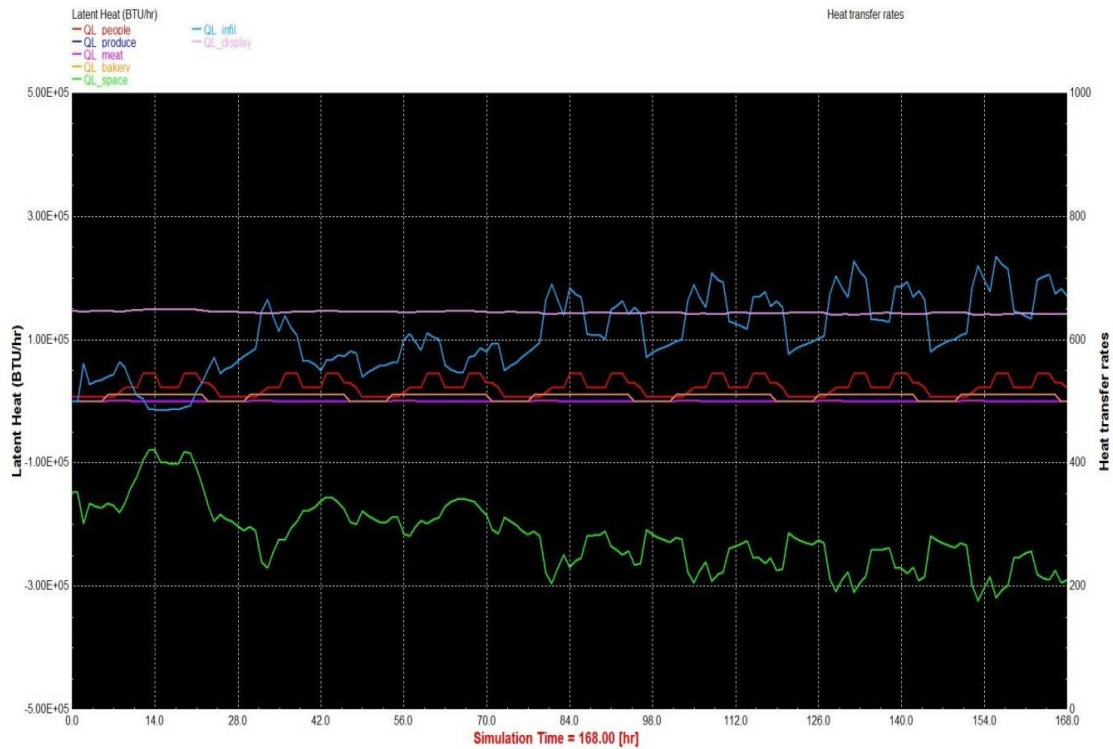


Fig. 17 Simulated heat balance using Thailand weather in TRNSYS

To firstly conduct zone interaction simulation, the AC constant in Fig. 15 is assumed based on Ref [6] using the latent load balance equation in Fig. 6. This simulation can generate the results which are nearly close to the measurement data in Ref [6]. As a result, the model is utilized to generate the zone conditions and latent load for Thai supermarkets by using Thailand weather in TRNSYS. The results are shown in Fig. 16 and 17 for zone relative humidity and each latent load components, respectively. The model is further calibrated via actual measurement from the first supermarket for verify the supermarket systems.

3.2 Fault detection analysis of energy interaction effect results

Step 1: Information collection

The stores are operated 24 hours a day and 7 days a week. Two main periods are categorized into occupied and unoccupied periods. The equipment of each supermarket functions similarly because all locations are the same retailer. The different features are: HVAC&R capacities and set points of routine operations are categorized in Table 3.

Table 3 Functions of HVAC&R machines

Equipment	Supermarkets controller functions
Evaporator coil temperature of low-temperature type	Low-temperature case, -31.7 to -26.1 °C for frozen foods

Evaporator coil temperature of medium-temperature type	Medium-temperature case, -12.2 to 1.7 °C depending on applications
Evaporator coil temperature of dual-temperature glass doors	Dual-temperature glass door, combination of 0.6 to 3.3 °C and -23.3°C for left and right sides, respectively.
Evaporator coil temperature of dual-temperature open cases	Dual-temperature open case, combination of 5 °C for reserving beverages, and another part for dry goods.
Display case control	Electrical thermal expansion valve based on a superheat temperature set point
Condenser fan control on the roof	On-off function based on measured condenser pressure
Compressor rack control	Sequential on-off compressors, based on suction pressure set points at each stage operation
HVAC Equipment	Controller functions
RTU control	Typical thermostat based on ZAT set point
DHU control	Typical IARH set point

Table 3 is tabulated for all HAVC&R equipment in each location. Refrigeration equipment has a vapor compression cycle, which includes a dry condenser and compressor-rack to supply refrigerant, 404A, in both medium and low temperature circuits of refrigerated display cases. The compressors are housed inside a store in a back room, whereas the condenser is on the roof. The centralized condenser unit is controlled based on the pressure set point of each fan stage. Five categories of display cases and two types of walk-in units are used in the supermarkets. The total power consumption of compressors from all freezers and coolers are monitored by the main power meters.

With a web-based user interface with the existing BAS in each store, OAT, IARH, and ZAT as driving force can be recorded versus metered power consumptions. To potentially validate and evaluate the performances, the same data set of five HVAC&R operations in Ref [2] are utilized to evaluate the proposed methodology of the present article. The data of the 5 supermarket buildings are summarized in Table 4.

Table 4 Measured data obtained from BAS [2]

Supermarket	DOE Climate	IARH (%)	OAT, °F (°C)	ZAT, °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, RCU, and ASH were recorded every 15 minutes at 5 locations			

Step 2: HVAC machine analysis

This step identifies the EST based on machine control operations. Two examples are given for normal and poor RTU functions.

Step 2.1 selects RTU energy consumptions and the OAT for the analysis in Store A to approximate the balance temperature as the EST point.

Step 2.2 demonstrates an example for RTU analysis in Store A. A preliminary plot between RTU energy consumptions and OAT is shown in Fig. 3. It shows the typical two energy lines of RTU operations, consisting of baseline energy and increased energy lines. 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 in an off-stage because the ZAT does not reach the set-point temperature. Whenever OAT is more than approximately 15.6 °C, 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 values. With a confidence of 0.05 (p value < 0.05), the improved r value of RTU energy consumptions and OAT are given in Table 5 (see Appendix)

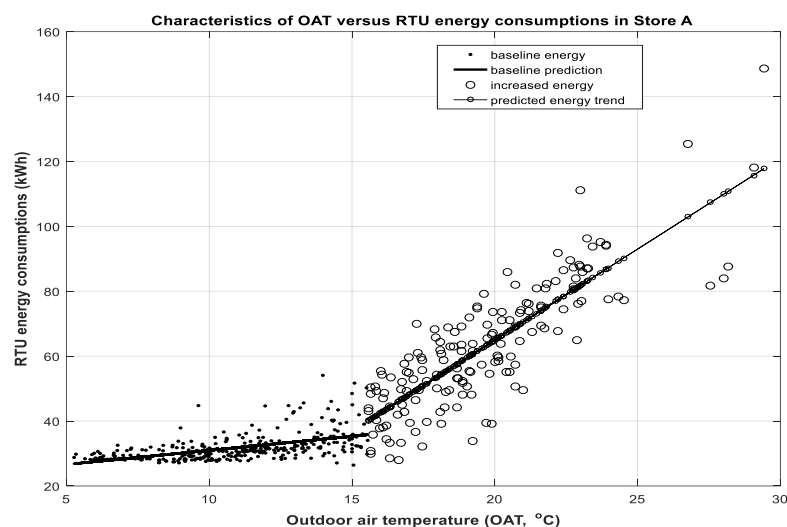


Fig. 18 EST point between OAT and RTU energy consumptions in Store A

Step 2.3 compares the computed value from Step 2.2, to compare with the results obtained from the simple interaction method. The improvement is shown in Table 5.

Table 5 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)
Ref [8]	0.742 (N)	0.434 (N)	0.692 (N)
Significant r value Difference findings by the improved method	RTU r value versus OAT of the proposed method is improved because baseline energy is excluded from the calculation. Only the active control area is used for the calculation. Meanwhile, a lower r value versus ZAT is caused by two-stage energy consumptions, in Fig. 9. In addition, r value of IARH is lower than the original value, referring to the RTU control which is independent to IARH. This		

In Fig.19, although the active control area ($OAT > 15.6\text{ }^{\circ}\text{C}$) is used to compute the new r value the outliers affect the r value versus ZAT. The r value is reduced from 0.692 to 0.597 because there are two linear lines. In Area 1 of Fig. 9, RTU energy consumptions more than 150 kWh which are outliers in Fig. 19a; however, they are second stage operations in Fig. 19b. At this significant point, outliers deviated from the main power line by considering periods of operations. As mentioned in the background, different store time operations may have different set points causing multiple power consumptions. Otherwise the outliers could be poor control performance or improper routine operations.

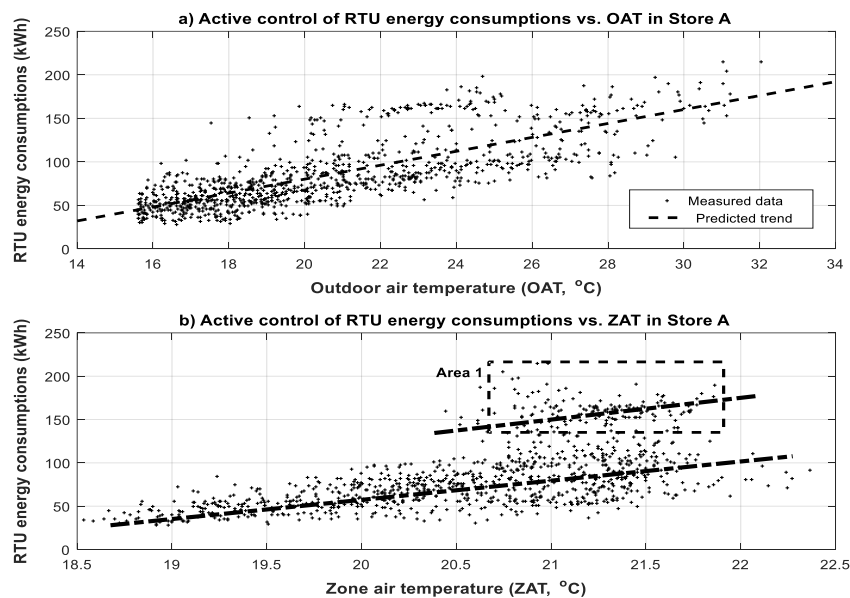


Fig. 19a) Active control area of RTUs versus OAT 19b) Active control area of RTUs versus ZAT

Step 3: Outlier identification

When the computed r values are less than the expected range in Table 1, set points are useful to assure that outliers are caused by different set points in different periods (occupied and unoccupied periods), not from faulty operations such as poor controllers. For controllers which are set inappropriately, the machine energy consumptions will deviate from the expected values of the normal system operations. Also, for different operational periods, set points may be adjusted or be wrongly set causing scattered energy consumption values. With these two different situations, three issues are required to be analyzed 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 and weekly analysis.

After the first two steps based on the whole data and EST point, Store A has acceptable operations because of the same routine operations. Baseline and increased power are analyzed concurrently. However, there are still some overlapping points between two power areas which do not dominate overall performance. Thus, Store A can be used as a baseline operation for other stores. To further identify applicable rule-based diagnosis approach for investigation enhancement, monthly data of the RTUs are further analyzed based on store-hour operations, as shown in Fig. 20.

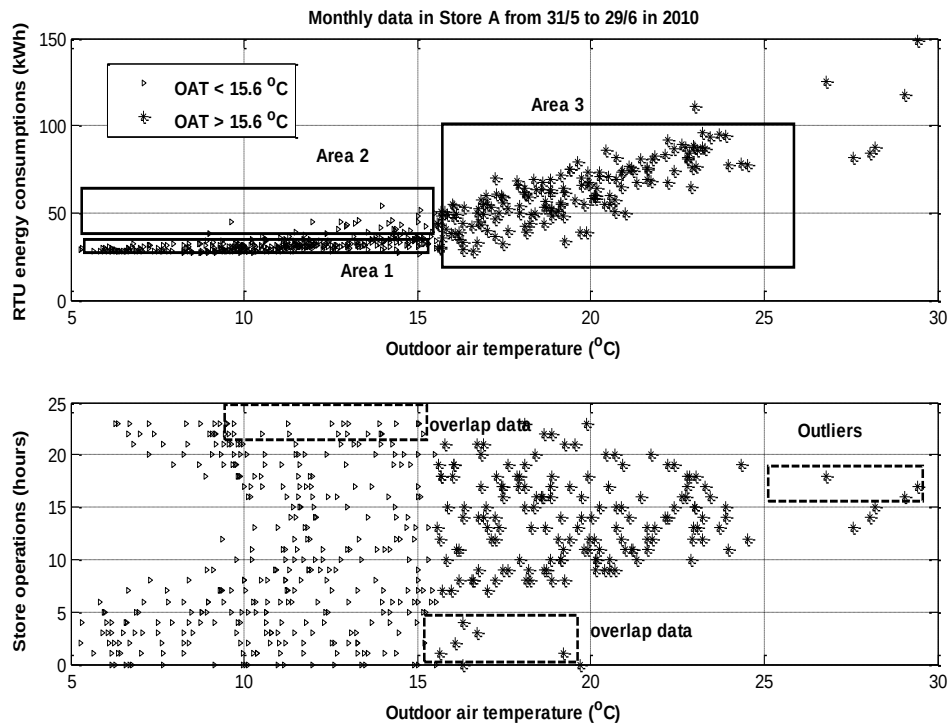


Fig. 20 Monthly data of RTUs and store operations versus OAT in store A

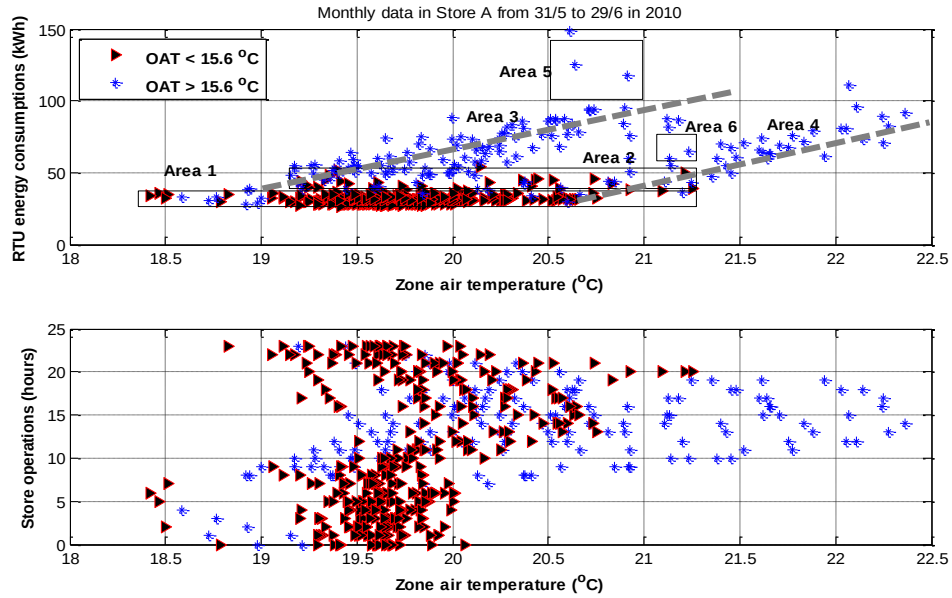


Fig. 21 Monthly data of RTUs and store operations versus ZAT for Store A

In Fig. 20, the blue points refer to store operation periods in which the OAT is more than the break point of EST (OAT > 15.6°C), whereas the red points are the rest of the operations when the OAT is less than the same point. In the figure, the RTU energy consumptions versus OAT can be isolated into three areas: 1) Area 1 - baseline energy in which the OAT is less than 15.6°C and store operations from 0:00 to 12:00; 2) Area 2 - baseline energy in which the OAT is less than 15.6°C and store operations from 12:01 to 23:00; and Area 3 - increased energy line in which the OAT is more than 15.6°C. However, there are some overlapping points between Area 2 and Area 3, caused by inaccurate identification of the EST point.

To further solve this issue, ZAT and RTU energy consumptions are plotted to identify the overlapping areas and other outliers. Based on the plot between ZAT and RTU energy consumptions, the four area characteristics can be defined as illustrated in Fig. 21; the first three areas are similar to Fig. 20. In the figure, Area 1 shows most of the ZAT points of the first 12 hours in which ZAT is varied between 18.5 and 21°C, whereas Area 2 shows the store operations from 12:00 to 23:00 while the OAT is less than 15.6°C in both areas. Area 3 has the ZAT from 19 to 21°C when the OAT is more than 15.6°C. With the same OAT range, Area 4 has the ZAT from 20.5 to 22.5 °C. Area 3 and Area 4 illustrate the two different set points of the store which are very useful to confirm the outliers in Areas 5 and 6. Although Area 5 is directly influenced by the high OAT (27 – 30 °C), it can be removed if the ZAT is set higher than the existing values (20.5 to 21°C). With energy consumptions in Area 6, the OAT and ZAT of Area 6 are close to Area 5. Also, the two

overlapping areas in Fig. 20 are shown by Fig. 21 to be the dead-band zones of Area 3 and 4, respectively.

Step 4: Faulty operation effects on RCU

This step further shows how abnormal or diagnosed operations of HVAC system can affect RCU energy consumptions and operations. With the same data in Store A, RCU operations are separated into two OAT areas. After that, the OAT of more than 15.6 °C area is firstly selected to plot RCU operations. In Fig. 22, RCU energy consumptions and store operations are plotted versus IARH using the same monthly data as Store A. It is apparent that the simple energy interaction method cannot be used to demonstrate significant outcomes because of the several set points of ZAT and IARH operations. To isolate the strong IARH effect to the plot between OAT or ZAT and RCU energy consumptions, the three IARH ranges (30-40%, 40-50%, and 50-60%) are fixed, to plot SLR as the following figures:

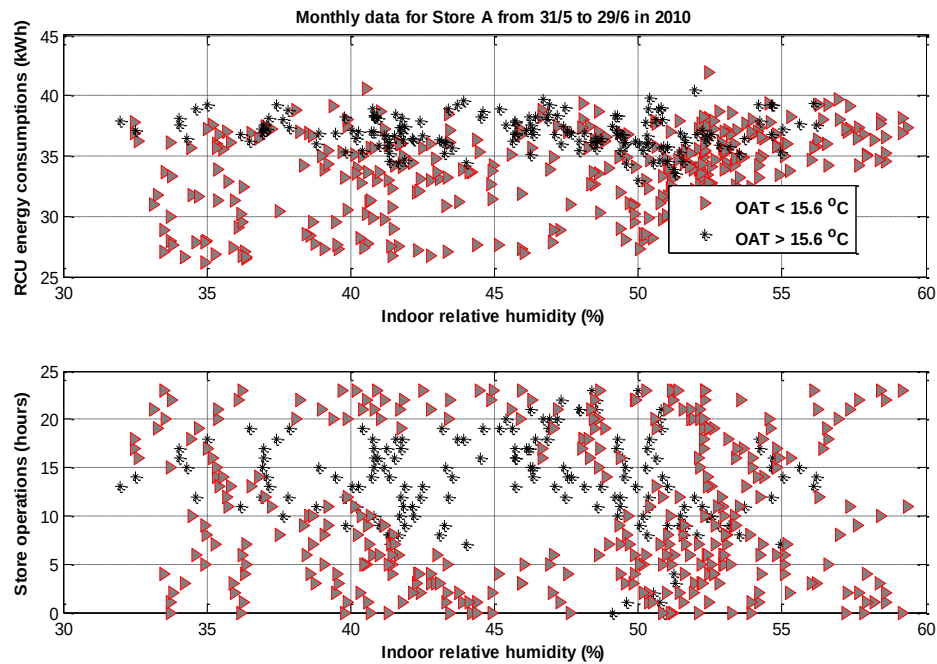


Fig. 22 Monthly data of RCU energy consumptions and store operations versus IARH for Store A

In Fig. 23 for OAT higher than 15.6°C, the three IARH ranges are plotted versus OAT, to locate the identified points of abnormal RTU operations. In the middle of Fig. 23, the three outliers can be located, leading to RCU energy consumptions of almost 38 kWh, with IARH between 40 and 50 %.

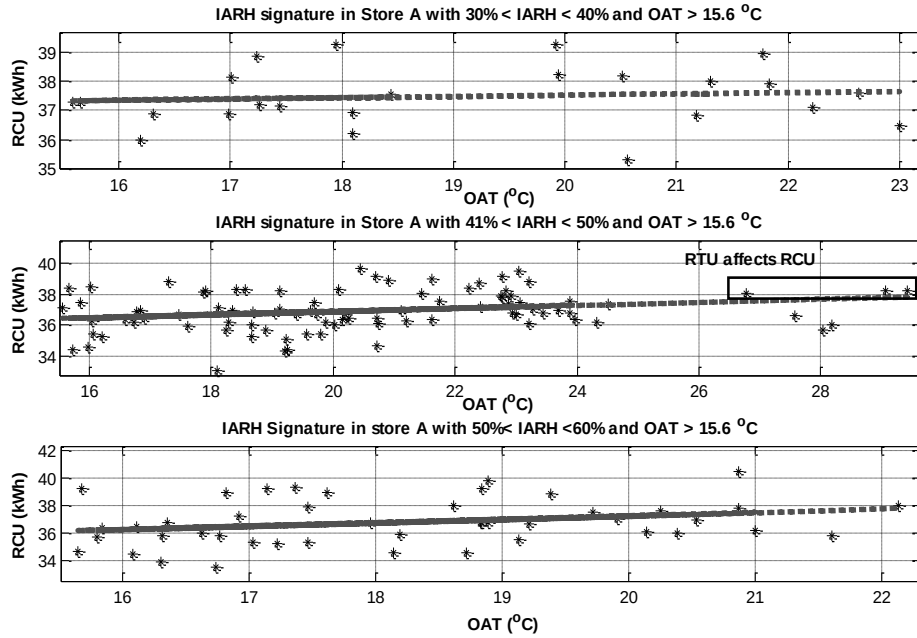


Fig. 23 Fixed IARH ranges of RCU energy consumptions versus OAT in Store A

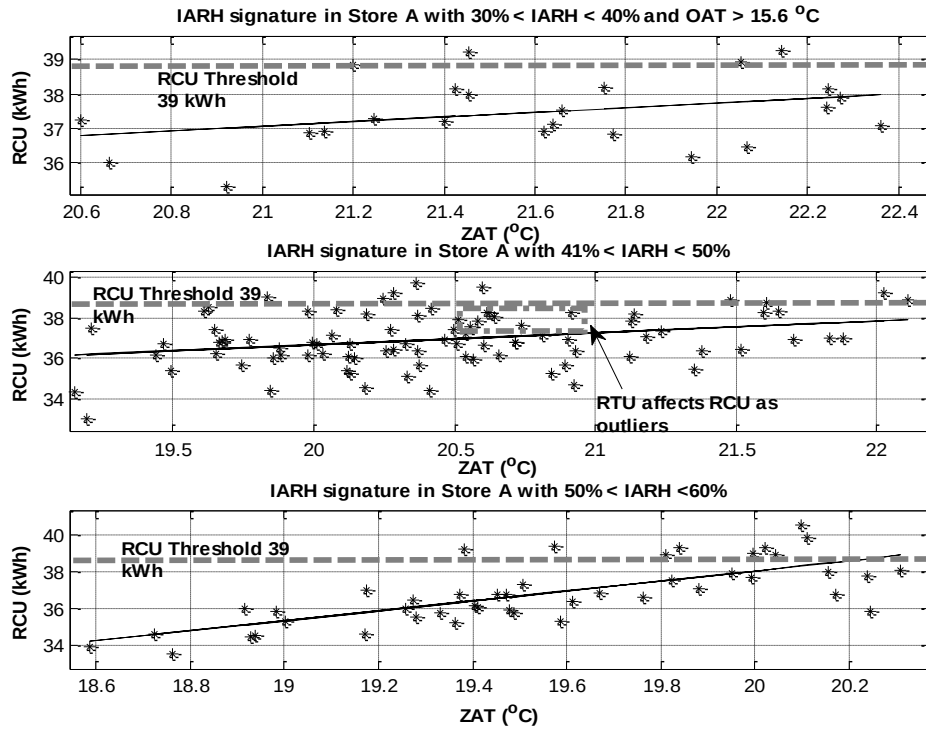


Fig. 24 Fixed IARH ranges of RCU energy consumptions versus ZAT in Store A

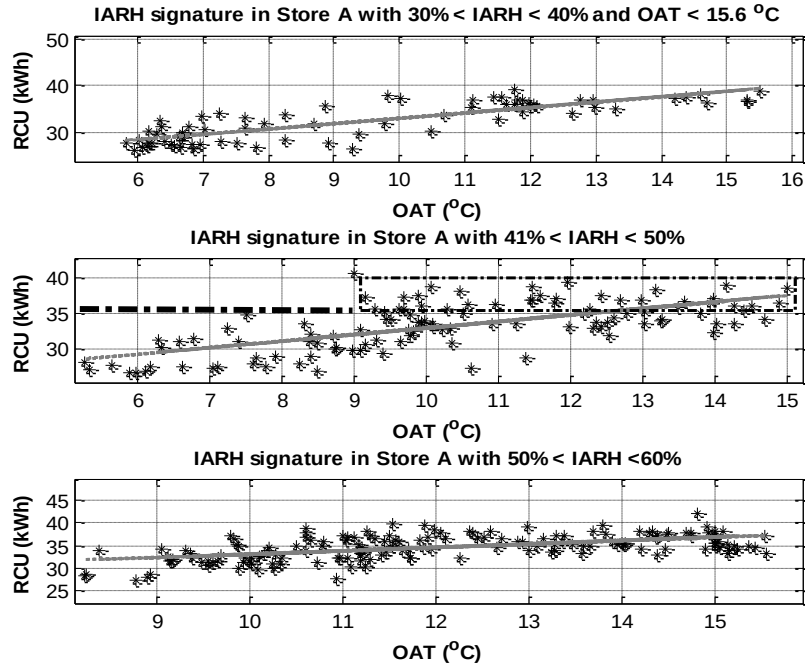


Fig. 25 Fixed IARH ranges of RCU energy consumptions versus OAT in Store A (OAT < 15.6 °C)

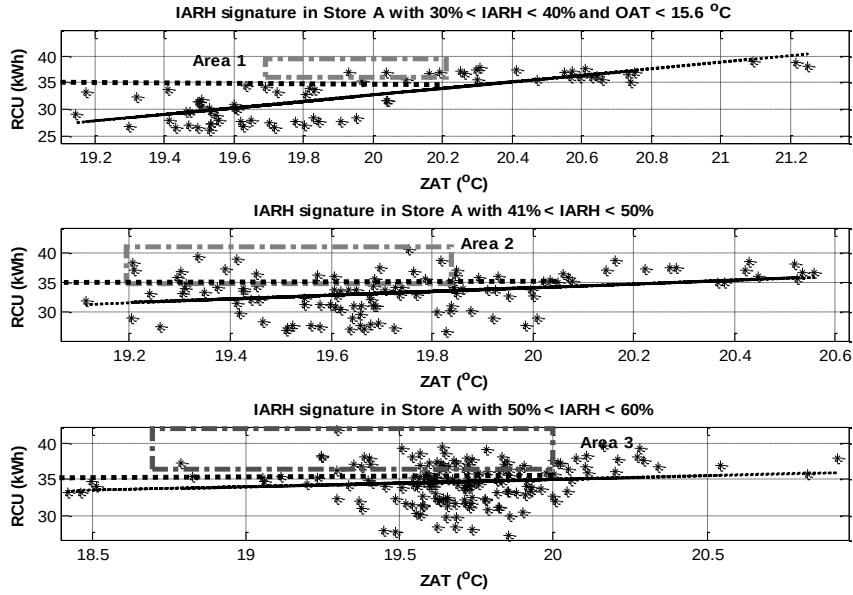


Fig. 26 Fixed IARH ranges of RCU energy consumptions versus ZAT in Store A (OAT < 15.6 °C)

The three points in Fig. 23 are further located in Fig. 24, which is a plot between ZAT and RCU energy consumptions with the same three IARH ranges. It can be noticed that the outliers of RTU operations have a ZAT between 20.5 and 21 °C and an IARH between 40 and 50%. These indoor conditions with almost the highest OAT of the monthly data set have almost the highest energy consumptions of about 38 kWh. Compared with the other high values in the same range, energy consumptions of about 39 kWh can be used as a threshold for the driving force conditions. With the

first three steps, the RTU operations in Store A work normally; however, when FDD for faulty interaction is applied to evaluate the corresponding effect on RCU operations in Step 4, the results show excessive energy use for RCU operations due to unsuitable indoor conditions provided by RTUs.

To further analyze the faulty interaction effect for $OAT < 15.6\text{ }^{\circ}\text{C}$, ZAT and IARH should be lower than the first case and RCU energy consumptions should be lower than 38 kWh, except for the IARH range which is not well-controlled. The overlapping areas of RTU operations on the ZAT plot (some blue points in Area 1 and black points in Area 2 of Fig. 21) affects RCU operations because a low OAT should cause a low ZAT; these two driving force conditions result in low energy consumptions of RCU. However, several outliers in overlapping areas due to higher IARH values than normal operations.

In Fig. 25, the faulty operations caused by Area 2 of RTUs versus ZAT are located in the black rectangle area. Although the OAT is less than EST with an IARH between 40 and 50%, they are outliers because the ZAT range is in the dead-band zone ($19.2 - 19.9^{\circ}\text{C}$ in Area 2 on the middle of Fig. 26). This finding of Area 2 can be used as the energy consumption threshold of about 35 kWh as in Areas 1 and 3 in Fig. 26. If the ZAT is less than $20\text{ }^{\circ}\text{C}$ and the IARH is less than 55 %RH, the OAT is less than the EST. It does not influence the energy consumptions of the RCUs more than the ZAT. To sum up, RTU operations work acceptably in Store A; however, with the FDD procedures, the operations cause outliers as excessive energy consumptions of RCU operations. The method can be applied for data cleaning of HVAC&R operations in supermarkets in near future research.

3.3 Data cleaning technique implementation

According to Fig. 18, the RTU compressors are staged on when the OAT is more than $15.6\text{ }^{\circ}\text{C}$ in Store A which is similar to Store B in the bottom of Fig. 4. However, there are malfunctions in the RTU operations of Store B, thus some skew data are deviated from the increased power consumption trend. First of all, OAT being more than $15.6\text{ }^{\circ}\text{C}$ is used to consider the RTU operations and to reduce some outliers from the raw data in the two stores.

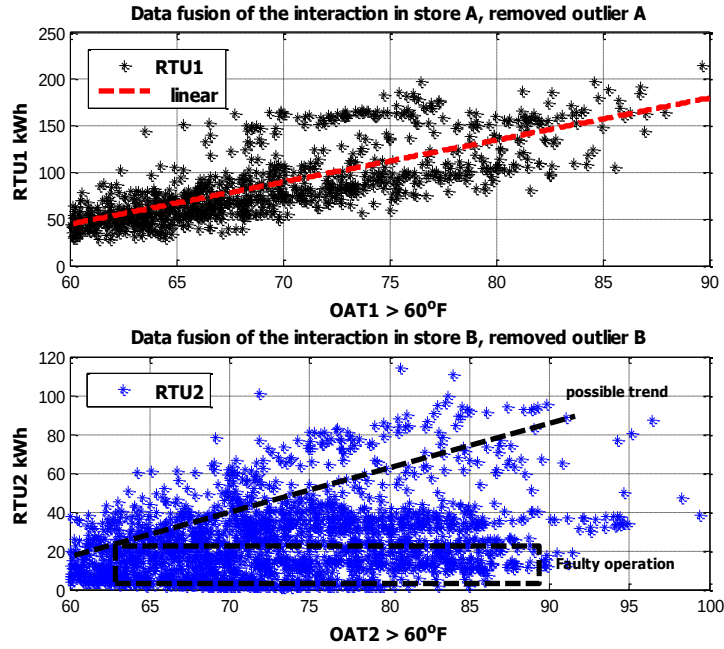


Fig. 27 Outlier removing of RTU kWh in Step 4 of Fig. 3

3.3.1 Z-score Implementation

Before computing Z score, an average and SD value of each data set are computed then are used to convert the data in Z score. Keeping z between -2 and 2, a new data set is determined and stored for analyzing energy interactions. Till now, step 1 to step 4 can be illustrated in Fig. 27.

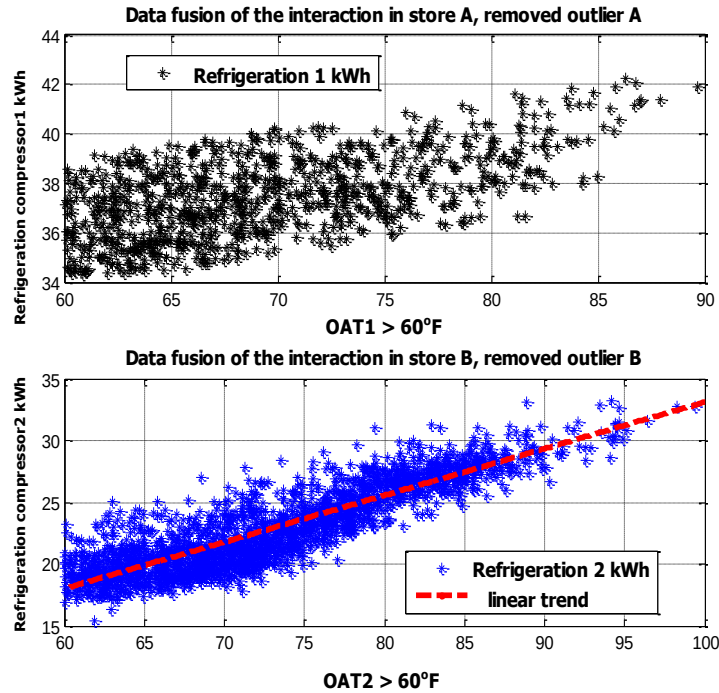


Fig. 28 Outlier removing of refrigeration kWh in Step 4

In Store A, it is clear that the linear line can be fitted from this data set relating to RTU operations versus OAT. Comparing the performance of Store, A to store B, there are still faulty

operations because several data points are lower than 20 kWh. There are at least two possible causes: 1) faulty sensors lead to the trend deviation and 2) RTUs are over designed severely; they lead to uncoordinated control of compressor operations and frequent compressor cycling at part load conditions. Therefore, refrigeration power consumptions are helpful to further decrease these fault effect based on IARH considerations.

3.3.2 Data Improvement via Consistent IARH Range

In Fig. 28, after removing outlier in Stores A and B, the relations of OAT and refrigeration power consumptions are almost linear function as one of the driving force conditions; however, with different IARH conditions, the data are still coupled with the IARH effect. Therefore, in step 5 of Fig. 3, the consistent IARH ranges - 30 – 40%, 41 – 50% and 51 – 60% are selected to significantly decouple IARH impact from OAT based on humidity control functions. These fixed IARH values can be utilized to identify some malfunctions as shown in Fig. 29. The two IARH ranges (30 - 40% and 41 – 50% IARH) of RTU2 are compared to an unconstrained IARH range of the RTU2. It can be seen that the different range operations significantly result in different data qualities.

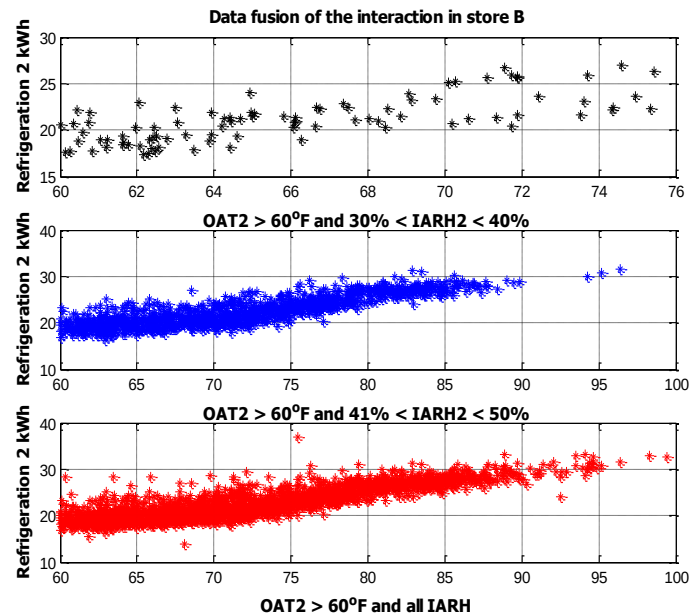


Fig. 29 Data Isolation via fixed IARH range in Store B

With the fixed IARH ranges and abnormal operations of the RTU 2 in Fig. 27, these two constraints can be used for improving the data fusion of RTU 2 as demonstrated in Fig. 30. Between 50 and 60% IARH, there are two-stage operations of RTUs leading to two linear lines, whereas the baseline power consumptions of the multiple fan operations are around 20 kWh. However, RTU operations still maintain suitable zone conditions in store B resulting in well-conditioned relation between refrigeration compressor energy consumptions and IARH2 at the same

fixed range. This multi-step data fusion is very helpful to potentially analyze abnormal operations of HVAC&R equipment.

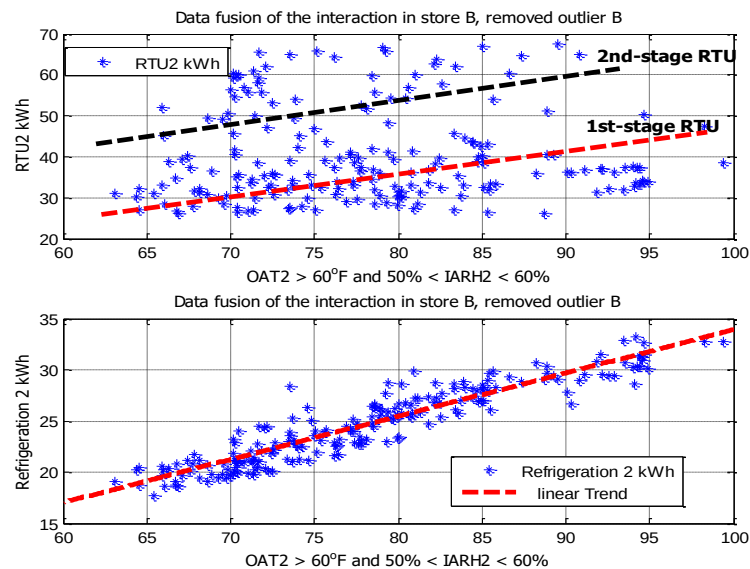


Fig. 30 Data Improvement in store B

3.4 Steady-state data implementation

Inefficient steady-state detector can be degraded if criteria are not robust enough. Especially, oversizing issue incurs in vapor compression cycle. This situation leads to longer start-up time and cycle loss. As a result, this happening reduces robustness of detector. Also, AFDD implementation is not efficient enough, thus efficient detector is so significant to be developed. TO be more specific in the large system, refrigeration system based compressor rack supplies refrigerant to multiple display cases. Improper valve selection also affects transient response of display cases. Tsh is as well as the set-point because it is used to control the valve operating. These preliminary results are improved by increasing of the operational information in Thailand or developing for adjusting TXV valve for reducing overcharge and compressor valve leakage.

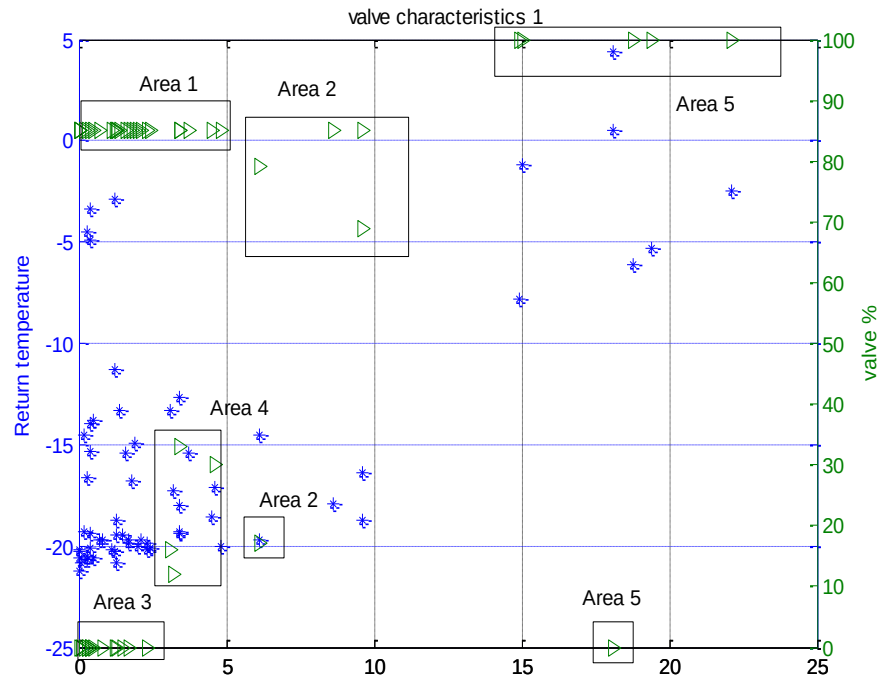


Fig. 31 Area categories of the TVX operations for a week in a Thai supermarket

From the two examples from display cases of the low-temperature compressor rack in Fig. 31 and 32, this consideration is very helpful to reduce poor or inexperienced commissioning in developing countries which still lack professional commissioning contractors. Although return temperature and superheat temperature are both the controlled variables for the efficient operations, steady-state detector cannot be designed effectively without the valve operation analysis because unsuitable operations cause fluctuated return temperature (Tr) and Tsh for the steady-state analysis. The Tsh versus valve opening percentage evidently shows at least five different areas in the Fig. 31 as follows:

- 1) Area 1 is identified for valve 85%, $Tsh < 5\text{ }^{\circ}\text{C}$ and $Tr > -20\text{ }^{\circ}\text{C}$. This full valve is operated too long. When valve is at maximum opening, supply temperature (Ts) still cannot satisfy the design temperature. Then Tsh is automatically changed to protect freezer which may be caused by fluctuation load of the open display case.
- 2) Area 2 is identified for valve 85%, $Tsh > 5\text{ }^{\circ}\text{C}$ and $Tr > -20\text{ }^{\circ}\text{C}$. This valve area is operated normally and linearly to satisfy the design temperature in the display case.
- 3) Area 3 is identified for valve 0%, $Tsh < 5\text{ }^{\circ}\text{C}$ and $Tr < -20\text{ }^{\circ}\text{C}$ in which the valve is stopped normally because Tsh is less than the set-point while the display case temperature or Tr being lower than the set-point temperature of the Tr .
- 4) Area 4 is identified for valve $> 10\%$, $Tsh < 5\text{ }^{\circ}\text{C}$ and $Tr > -20\text{ }^{\circ}\text{C}$ in which the valve starts open normally.

- 5) Area 5 is identified for non-commissioning process leading to valve opening is high than 85%.
- 6) Beyond the four cases, Area 6 is further defined for valve 0 %, $T_{sh} < 3\text{ }^{\circ}\text{C}$ and $T_r > -20\text{ }^{\circ}\text{C}$. This area is reverse control action from Area 1; it may be caused by system fluctuation or unsteady-state operations

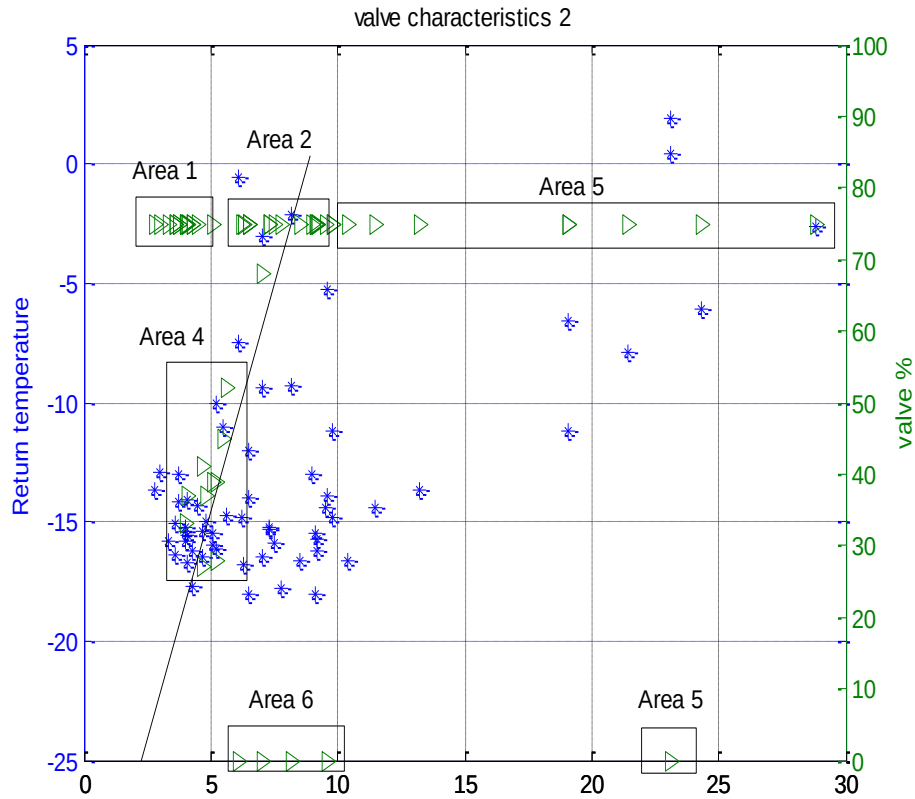


Fig. 32 Area categories of another TVX valve for a week in the same Thai supermarket

Similar to Fig. 31, Fig 32 shows the valve characteristic operations in a different display case. Six areas can be defined with the different T_{sh} ($2\text{ }^{\circ}\text{C}$) setting and maximum valve operation (75%). With the set-point information on the controller, we found that $6\text{ }^{\circ}\text{C}$ with minus 2 degrees Celsius ($4\text{ }^{\circ}\text{C}$) should be the proper control point to protect compressor valve leakage and overcharge caused by non-vaporized refrigerant or liquid status moving to the compressor rack.

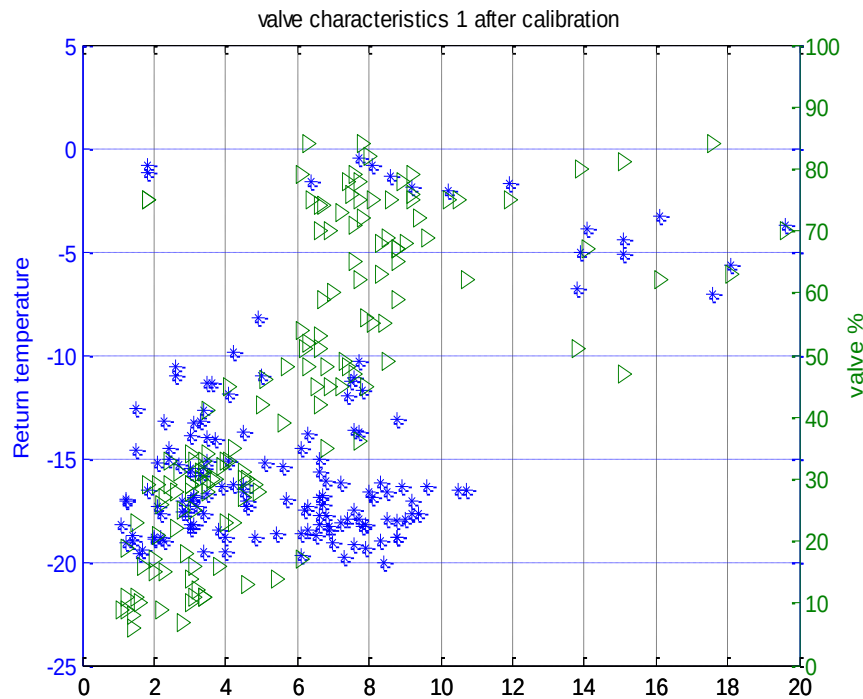


Fig. 33 Improved data for one-month raw data of the same supermarket in Fig. 32

To further test the performance of the analysis with the defined areas as the rule-based development, the data of one month are used; the results are depicted in Fig. 33 with two y-axis comparisons between T_r and valve operations. With the potential performance, the technique can be further used to improve the steady-state design in the literature review [7] which summarized that T_{sh} and T_r are both effective to consider the steady-state performance of the centralized refrigeration system.

3.5 FDD design results

Refer to Wichman and Braun [3], the parameters of the report are improved from the existing monitoring system in the cases study. Meanwhile, FDD in refrigeration systems includes simultaneous diagnostics based on fault-free data; however, it is handicap to follow the method. Fault-free data are not available in centralized refrigeration system. To reduce the problem, the interactions between load operations and related parameters in vapor compression cycle in RP 1043 are developed as preliminary tool to compare abnormal operations in refrigeration system. The load comparisons are used to compare each operation for detecting and diagnosing typical faults. As a result, FDD based load comparison condition, according to the typical faults summary in Table 6, is an alternative approach for diagnosing typical faults in the refrigeration system. In this report, three diagnosed faults are demonstrated as the examples including evaporator fouling and non-condensable.

Table 6 Typical faults on a refrigeration system

Typical faults refrigeration system	Simple criteria for load comparison consideration
F1: Condenser fouling	Condenser airflow rate (Ma) calculation
F2: Evaporator fouling	Evaporator airflow rate calculation
F3: Refrigerant undercharge	$T_{sc} - T_{sh}$ is more than zero when load capacity is compared.
F4: Refrigerant overcharge	$T_{sc} - T_{sh}$ is less than zero when load capacity is compared.
F5: Compressor valve leakage	T_{dis} of measurements – T_{dis} of normal operations are more than zero.
F6: Liquid-line restriction	Check temperature drop across dry filter (not considered)
F7: Non-condensable gas	T_{cond} is higher when load capacity is decreased.

F2 for evaporator fouling from the decouple based feature in both RTU and self-contained cooler, air mass flow rate of the normal operations or manufacturing data are used to compare to the computed value based on the available measurement using a simple heat balance equation. However, in Thailand, these data are seldom available to obtain from manufacturer. To this end, Ma is calculated from the same heat balance equation and then will be compared with each load capacity operation. For typical normal operations, in case of the existing F2, higher load operations lead to lower Ma because fouling results in higher different air temperature ($T_r - T_s$). As a result, three figures are conducted as shown in Fig. 34, 35 and 36 for computed Ma in the first and second display cases, for interaction in terms of linear relation (slope is Ma) between load and Ma in the first and second display cases and for possible diagnosed F2 using the notification of Ma variations versus load and T_r , respectively.

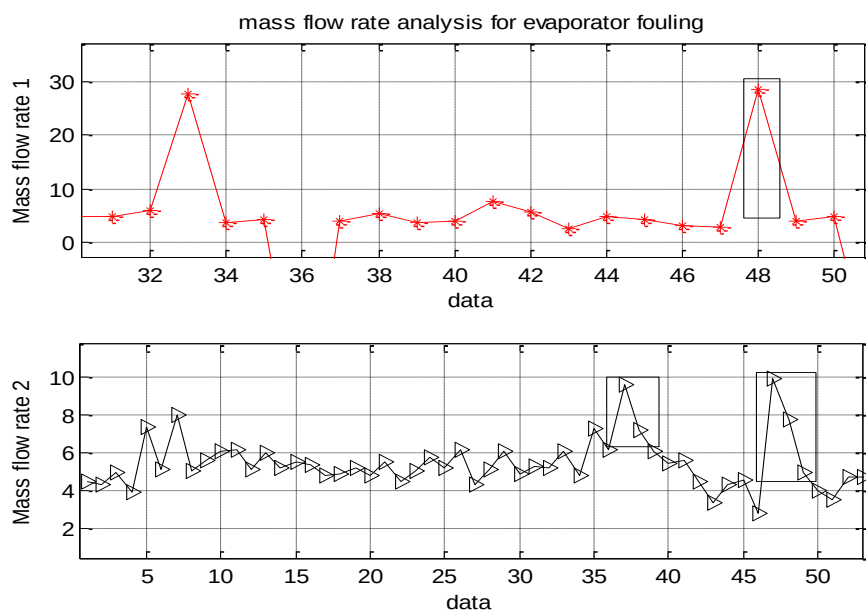


Fig. 34 computed Ma in the first and second display cases

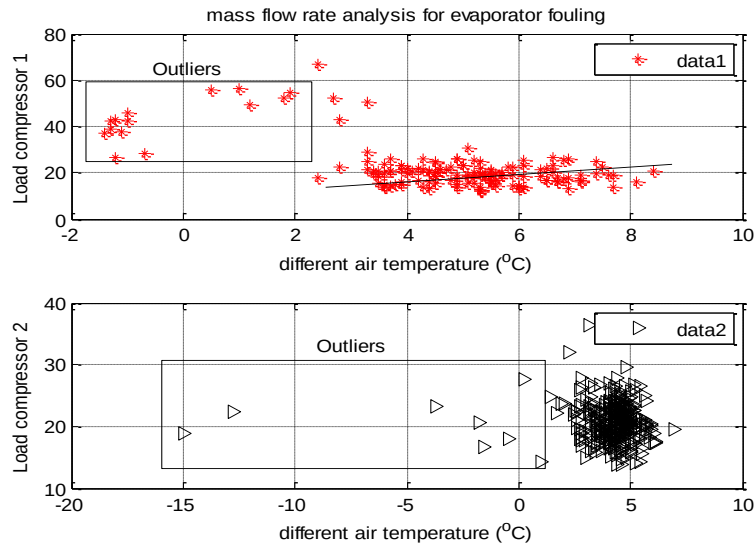


Fig. 35 interaction between load and Ma in the first and second display cases

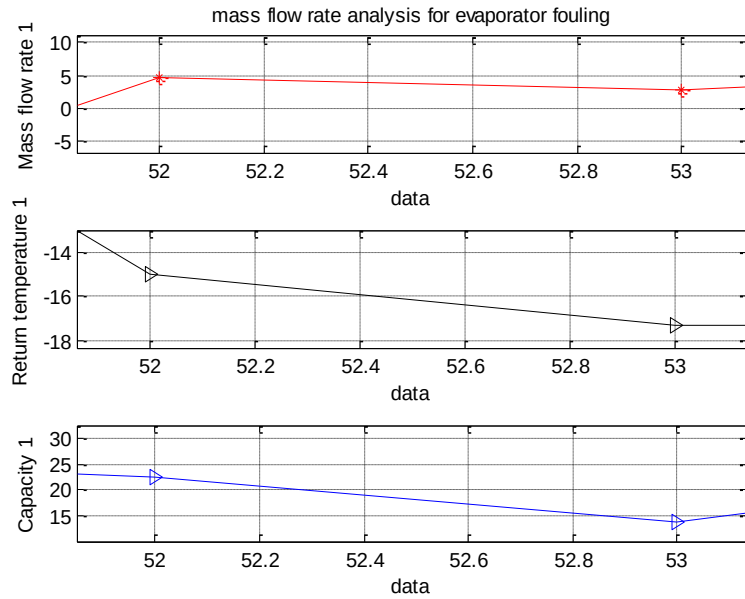


Fig. 36 diagnosed F2 using the notification of Ma variations versus load and Tr

In Fig. 34, there are some outliers occurred by stopped compressor; however, load operations are predicted by the polynomial equation recommended by the refrigeration manufacturer. As a result, the outliers should be mitigated before using load comparisons versus computed Ma from the heat balance equation. To further study the linear trend between load and temperature difference ($T_r - T_s$) in the display cases, Fig. 35 shows simple linear relation; we found that estimated Ma is quite fluctuated due to load fluctuation and outliers. To reduce this effect, Fig. 36 diagnosed F2 using the notification of Ma variations versus load and Tr. In the figure, F2 occurs because Tr normally decreases causing higher temperature difference and higher load operations

to keep Ma constantly. However, the load is reversely reduced because fouling or ice-making obstructs air flow rate.

F7 for non-condensable gas from the decoupling based feature in a RTU using Tcond as the fault signature identification, it implies that load increase is proportional to higher Tcond in case of normal operations.

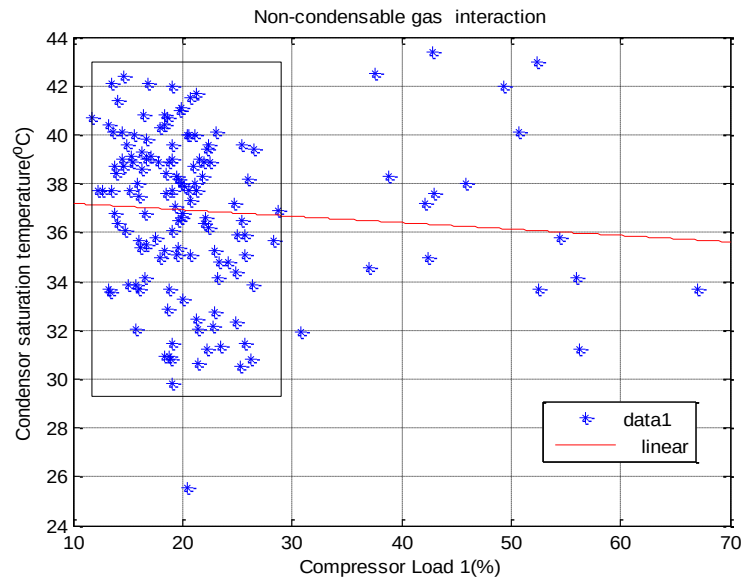


Fig. 37 Interaction between load and Tcond

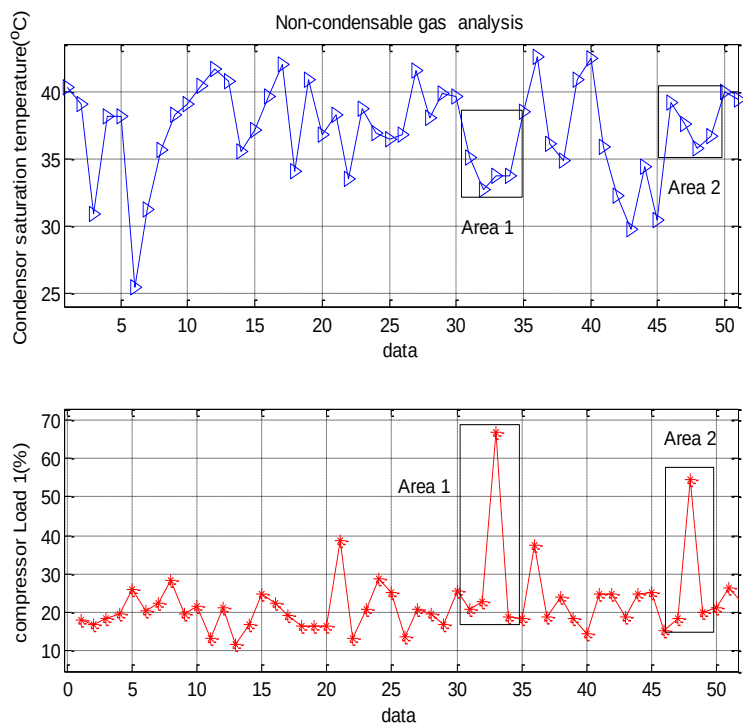


Fig. 38 time data of load and Tcond to identify F7

However, in Fig. 37, the findings are that the linear trend is negative due to some data are reversely incurred because Tcond is too high when load is low. To be more specific, Fig. 38

evidently shows that T_{cond} is higher when load capacity decreases in Area 1 and 2. This happening is non-condensable gas effect.

5. Conclusion and Discussion

Although FDD has been used in supermarket equipment for sustainable energy savings and suitable preventive maintenance caused by sudden and degradation faults, no previous study investigates the effect of faulty HVAC operations on refrigeration system operations. In addition, full procedures have been seldom developed for integrated HVAC&R energy systems. As a result, robustness and reliability of existing approaches could not be achieved in commercial supermarkets. To enhance FDD robustness and performance for refrigeration systems, this project proposes the four procedures composing of: 1) fault detection analysis of faulty interaction effect on refrigeration operations; 2) a data cleaning procedure to improve data quality of HVAC&R operations; 3) a novel steady-state detector based on refrigerated display case operations; and 4) decoupling-based features applied in the compressor-rack refrigeration system. The first three steps are mainly used to improve data quality obtained from the field data. Using the full data cleaning process, the decoupling-based method is applied to possibly investigate fault diagnostics. The results show that the proposed method can improve data quality which potentially leverage the FDD approach without using fault-free data. From the investigations, the four typical faults (evaporator and condenser fouling, non-condensable and compressor valve leakage) can be diagnosed without additional sensors installed on the compressor-rack system. However, the robustness and reliability of the proposed techniques can be improved via more field test data and manufacturing data for further developing as an effectively real-time diagnostic system embedded into a current remote monitoring system.

6. Output of this report

Researches published on the proceeding of the International conference

- D. Woradechjumroen. Investigations of faulty interaction effect to refrigeration system operations, in: Proceedings of the 8th TSME International Conference on Mechanical Engineering (TSME - ICOME), Thailand, 2017.
- D. Woradechjumroen, T. Tongshoob. Data Fusion Technique for Leveraging Reliability of Supermarket Field Data, in: Proceedings of the 7th TSME International Conference on Mechanical Engineering (TSME - ICOME), Thailand 2016.
- D. Woradechjumroen. Smart Building Energy Solutions Technologies – Possible Implementations in Thailand Supermarkets, in: Proceedings of the 7th TSME International Conference on Mechanical Engineering (TSME - ICOME), Thailand 2016

Researches published on ISI International Journal (under review)

Fault detection analysis of energy interaction effect for HVAC&R operations in commercial supermarkets (under review on Energy and Buildings – Journal Ref: ENB_2018_1429)

Research Utilization in Commercialization

The method in the report is being proposed and verified as FDD standard analysis for sustainable energy savings and predictive maintenance in Thai commercial supermarkets by Air Conditioning Engineering Association of Thailand (ACAT) and Thai Refrigeration Association (TRA).

7. References

- [1] K. Barlish, K. Sullivan. How to measure the benefits of BIM — a case study approach, *Automation in Construction* 24 (2012) 149–159.
- [2] 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.
- [3] A. Wichman, J.E. Braun. Fault detection and diagnostics for commercial coolers and freezers. *Interactional Journal of HVAC&R Research* 15(1) (2009) 77-99
- [4] H. Li, J.E. Braun. Decoupling features and virtual sensors for diagnosis of faults in vapor compression air conditioners *International Journal of Refrigeration* 30(3) (2007) 546–64.
- [5] B. Dong, M. Gorbounov, S. Yuan, T. Wu, A.Srivastav, T. Bailey, Z.O. Neill. Integrated energy performance modeling for a retail store building. *Building Simulation* 6 (2013) 283 – 295.
- [6] A. Bahman, L. Rosario, M.M. Rahman. Analysis of energy savings in a supermarket refrigeration/HVAC system, *Applied Energy* 98 (2012) 11-21
- [7] Yu, Y., Woradechjumroen, D., Yu, D. A Review of Fault Detection and Diagnosis Methodologies on Air-handling Units. *Energy and Buildings* 2014; 82:550-562.
- [8] M.S. Breuker, Evaluation of a statistical, rule-based fault detection and diagnostics method for vapor compression air conditioners. Master's thesis, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana.
- [9] M.S. Breuker, J.E. Braun. Common faults and their impacts for rooftop air conditioners. *International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research* 4(3) (1998) 303-318.
- [10] M.S. Breuker, J.E. Braun. Evaluating the performance of a fault detection and diagnostic system for vapor compression equipment. *International Journal of HVAC&R Research* 4(4) (2009) 401-425.
- [11] H. Li, J.E. Braun. An economic evaluation of automated fault detection and diagnosis for rooftop air conditioners, in: *Proceedings of the International Refrigeration and Air Conditioning Conference*, 2004.
- [12] H. Li, J.E. Braun A methodology for diagnosing multiple-simultaneous faults in vapor compression air conditioners, *International of HVAC&R Research* 13(2) (2009) 369–95.
- [13] J. Garcia, L. Coelho. Energy efficiency strategies in refrigeration systems of large supermarkets, *International Journal of Energy and Environment*, 3(4) 2010.

- [14] H. Li, J.E. Braun. Automated fault detection and diagnostics of rooftop air conditioners for California, Ray W. Herrick Laboratories, Purdue University Final Report for the Building Energy Efficiency Program, California Energy Commission. August 2003.
- [15] H. Li, J.E. Braun Evaluation of a decoupling-based fault detection and diagnostic technique-part II: field evaluation and application, Journal of Harbin Institute of Technology 13 (2006) 164-171.
- [16] D.W. Taylor, D. W. Corne, D. L. Taylor, J. Harkness. Predicting alarms in supermarket refrigeration systems using evolved neural networks and evolved rule sets, in: Proceedings of the World Congress on Computational Intelligence. IEEE Press, 2002.
- [17] D.W. Taylor, D. W. Corne. An investigation of the negative selection algorithm for fault detection in refrigeration systems, in: Proceedings of International Conference on Artificial Immune Systems, 2003.
- [18] R. Fisera, P. Stluka. Performance monitoring of the refrigeration system with minimum set of sensors, World Academy of Science, Engineering and Technology, International Scholarly and Scientific Research & Innovation 6 (7) (2012).
- [19] N. Ren, J. Liang, B. Gu, H. Han. Fault diagnosis strategy for incompletely described samples and its application to refrigeration system, Mechanical systems and Signal Processing 22 (2008) 436-450.
- [20] K. Assawamartbunlue, M.J. Brandemuehl. Refrigerant leakage detection and diagnosis for a distributed refrigeration system, International Journal of HVAC&R Research 12 (3) (2006) 389-405.
- [21] Z. Yang, K.B. Rasmussen, A.T. Kieu, R.I. Zamanabadi. Fault detection and isolation for a supermarket refrigeration system – part one: kalman-filter-based methods, in: Proceedings of the 18th IFAC World Congress, Milano (Italy), 2011.
- [22] Z. Yang, K.B. Rasmussen, A.T. Kieu, R.I. Zamanabadi. Fault detection and isolation for a supermarket refrigeration system – part two: unknown-input-observer method and its extension, in: Proceedings of the 18th IFAC World Congress, Milano, Italy, 2011.
- [23] G. Liu, M. Liu. A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems, Building and Environment 46 (2011) 409-420.
- [24] M. Kim, S.H. Yoon, P.A. Domanski, W. V. Payne. Design of a steady-state detector for fault detection and diagnosis of a residential air conditioner, International Journal of Refrigeration 31 (2008) 790 – 799.

8. NOMENCLATURE

AC = air-conditioning unit

ASH = anti-sweat heater

AHU = air-handling units

BAS = building automation system

COP = coefficient of performance (COP).

DHU= dehumidification Unit

EST = energy signature temperature (°C)

F = faulty operations

FDD = fault detection and diagnosis

HVAC = heating, ventilation and air-conditioning

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

IARH = indoor relative air humidity, %

MBCx = monitoring-based commissioning

N = normal operations

OAT = outdoor air temperature, °C

P = pressure sensor

Psuc = suction pressure

RCU = refrigeration compressor rack unit

r value = Pearson's correlation

RTU = rooftop unit

SLR = simple linear regression

T = temperature sensor

Tcond = condenser saturation temperature

Tdis = discharge Temperature

Tr = return temperature (Tr)

Ts = supply temperature

Tsc = sub-cooling temperature

Tsh = superheat temperature

TXV = thermostatic expansion valve

WUI = web-based user interface

ZAT = zone air temperature, °C

α = level of significance