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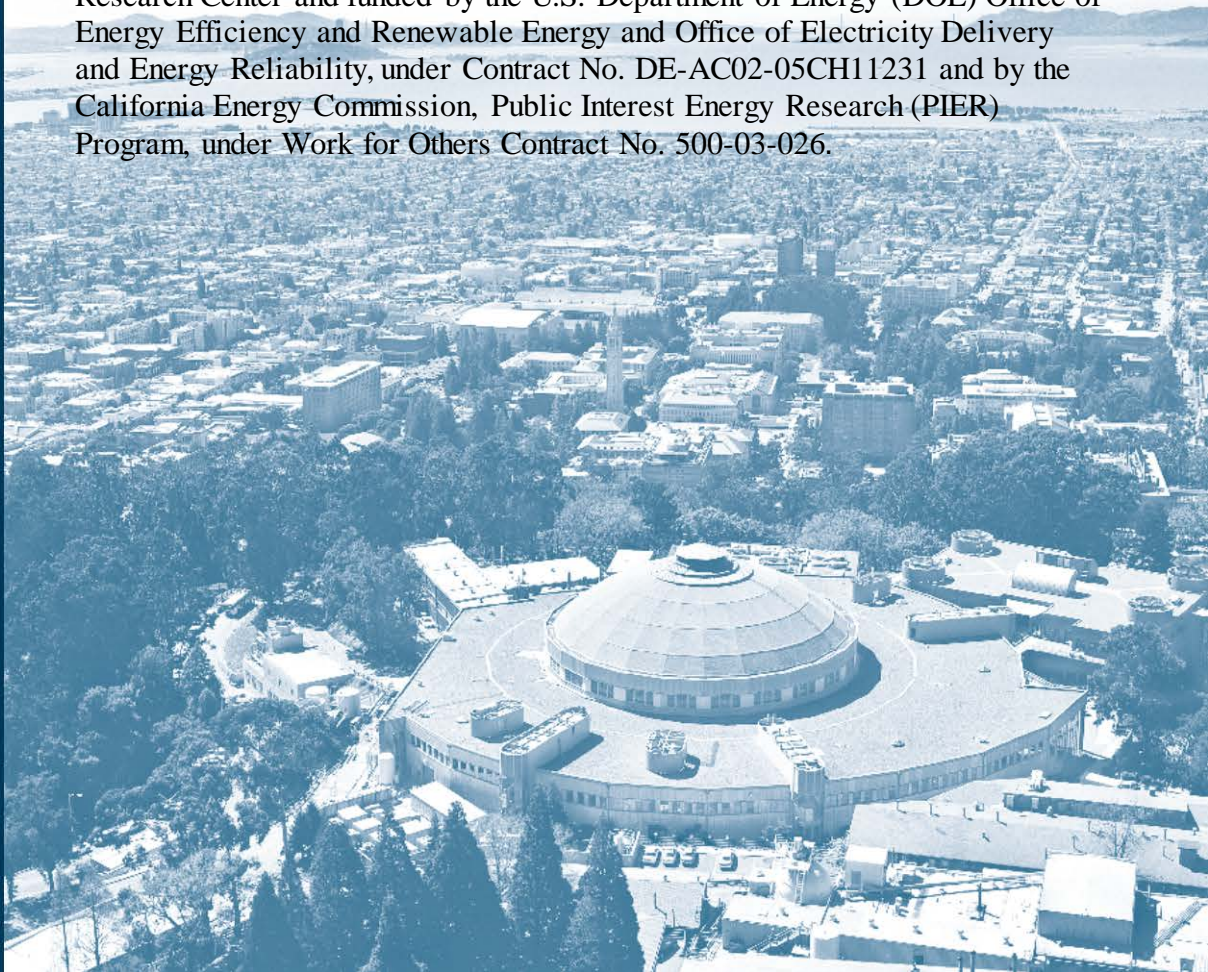
DEVELOPMENT AND VALIDATION OF DEMAND RESPONSE QUICK ASSESSMENT TOOL FOR REFRIGERATED WAREHOUSES IN CALIFORNIA

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Renewable Energy Technologies
- Transportation

Development and Validation of Demand Response Quick Assessment Tool for Refrigerated Warehouses in California is the final report for the PIER project (contract number 500-03-026, work authorization number 3) conducted by the Demand Response Research Center. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The goal of this project was to develop a Demand Response Quick Assessment Tool for Refrigerated Warehouses (DRQAT-RW) that can make accurate recommendations about Energy Efficiency (EE) and Demand Response (DR) potential in individual facilities. The objective of this tool is to provide a reliable way for simulating the operations of individual refrigerated warehouse facilities. This report discusses EE measures, DR considerations, and load shed or shift strategies relevant to refrigerated warehouses. In addition, the EnergyPlus model used as the simulation engine of the tool is described in detail. The report also analyses the measured data from an actual cooler facility in Southern California to verify the simulation results of the tool.

DRQAT-RW was tested and validated at an actual cooler facility in southern California. An analysis on the measured and simulated space temperature resulted in acceptable tolerance values suggesting that even without model calibration DRQAT-RW's simulation engine is capable of predicting accurate space temperature. In addition the model accurately predicted 1.5°F temperature increase due to a DR event at the test facility. The predicted temperature rise precisely represents the facility's behavior during an actual event during which 9 probes collected real-time space temperature. The estimated demand reduction during the two hour DR event is 157 kW, which is very close to the measured load shed based on the baseline days of 3/17/2015 and 3/18/2015. It was found that the compressor load had large fluctuations before and after the DR test day. Using the average demand of all baseline days, the simulated load shed from compressor load is 20% higher than the measured on the DR test day, which is still within the acceptable model tolerances.

Keywords: Refrigerated Warehouse; Demand Response; Food Storage; Food Transportation;

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EXECUTIVE SUMMARY

Introduction

Demand Response is a set of strategies used to manage demand-side load on the electric grid as a way to balance the supply and demand of electricity. Refrigerated warehouses present an opportunity to shift a significant amount of electric demand, but they also exhibit unique system, operational, and control challenges that must be addressed before a DR strategy can be safely and effectively implemented. Refrigeration loads account for a significant portion of the facilities' total energy usage, their usage is often greatest during utility peak periods, and the thermal mass of the stored product in the insulated spaces can often tolerate reduced cooling capacity for a few hours when needed.

From 2010, the Demand Response Research Center (DRRC) started to explore demand response opportunities in industrial refrigerated warehouses in California. Previous studies demonstrated that industrial refrigerated warehouses are very good candidates for undertaking energy efficiency (EE) and demand response (DR) measures to manage their electricity use. The demand response potential from the sector of industrial refrigerated warehouses in California is quite large (estimated DR potential of 45-90MW based on the installed load capacity 360MW in 2008).

Project Purpose

The purpose of this project was to:

- Provide an overview of the energy efficacy and demand response measures in industrial refrigerated warehouses, with a focus on the demand response considerations of load-shifting and load-shedding strategies;
- Develop the refrigerated warehouse prototype model for simulating the EE and DR measures' performance;
- Develop a demand response quick assessment tool for use in refrigerated warehouses;
- Validate the prototype model using measured data from an actual refrigerated warehouse facility.

Project Results

The research team conducted a comprehensive review of previous studies on the EE and DR measures in refrigerated warehouses. The findings are summarized below:

- The measures of precooling, refrigeration system capacity limiting and battery charging management are very effective for load shifting in refrigerated facilities.
- The refrigeration system (compressors, condensers, and evaporators) is the single largest energy consumer at a refrigerated facility. Significant load shed can be achieved by complete refrigeration system shutdown during DR event hours.
- Cycling off air-handling units (AHUs) can provide fast demand response without impacts on the stored food.
- The control strategy of "Increase Space Temperature Setpoint" is effectively similar to shutting down the refrigeration system—the refrigeration compressors simply turn off

(or reduce capacity if serving other refrigeration loads) until the space temperature rises to the new higher setpoint, at which time the compressors will turn back on.

The refrigerated warehouse prototype modeling results and the field study show that:

- Demand Response Quick Assessment Tool for Refrigerated Warehouses (DRQAT-RW) can accurately estimate the effect of various EE and DR measures in a refrigerated warehouse.
- An analysis on the measured and simulated load demand and space temperature resulted in acceptable tolerance values suggesting that even without model calibration, DRQAT-RW is capable of predicting accurate space temperature and demand in refrigerated warehouses.
- The model's predictions of refrigeration system demand show an acceptable agreement with the measured data (NMBE and CV(RMSE) for this comparison are 4.7% and 18.8%, respectively).
- The estimated demand reduction during for a two hour DR test event was 157 kW and the maximum load shed achieved during an actual DR test was 126kW. The actual load shed was 20% lower compared to the DRQAT-RW estimate.

Project Benefits

The key deliverable of this study is the development of the Demand Response Quick Assessment Tool for Refrigerated Warehouses. Benefits of this tool are:

- Predict technically and economically viable EE and DR projects in individual facilities,
- Simulate the operations of individual facilities to reduce project implementation risks
- Develop a better understanding of how refrigerated warehouse facilities react to changes in conditions,
- Facilitate greater adoption of DR in refrigerated warehouses.

This tool will help users to:

- Understand under what conditions facilities can shift or shed load and where they can implement changes to existing systems to enable them to do so.
- Develop a better understanding of energy savings opportunities and DR capabilities from optimizing operating conditions.
- Develop a statistical relationship between pre-cooling and "drift" that can be rationalized into a risk management strategy with predictable constraints for operators.
- Establish "best practices" and a defined strategic plan matrix for site owners and operators in this sector based on project data and outcomes.
- Help identify cooling technology upgrades that demonstrate best return on investment
- Develop general guidelines of return on investment for a range of energy saving opportunities in refrigerated warehouses.
- Build a better set of financial analyses and performance metrics to describe the full range of investment benefits for the customer to simplify the decision-making process and increase adoption rates.

CHAPTER 1: Introduction

1.1 Background

This report covers the previous studies about Energy Efficiency (EE) and Demand Response (DR) in individual refrigerated warehouses and the use of the refrigeration system for peak demand reduction. DR is a set of strategies used to manage demand-side load on the electric grid as a way to balance the supply and demand of electricity. Refrigerated warehouses present an opportunity to shift a significant amount of electric demand, but they also exhibit unique system, operational, and control challenges that must be addressed before a DR strategy can be safely and effectively implemented. Refrigeration loads account for a significant portion of the facilities' total energy usage, their usage is often greatest during utility peak periods, and the thermal mass of the stored product in the insulated spaces can often tolerate reduced cooling capacity for a few hours when needed.

The Demand Response Research Center (DRRC) at Lawrence Berkeley National Laboratory (LBNL) has tested demand response actions in four refrigerated warehouses during the summer of 2007 (Lekov et al., 2009), and evaluated the effectiveness of energy-efficiency retrofits and demand response strategies from eleven case studies of industrial refrigerated warehouses. In 2011, the DRRC presented an overview of the potential for load sheds and shifts from electricity use in response to DR events, along with physical configurations and operating characteristics of refrigerated warehouses (Sasank et al., 2011). Refrigerated warehouses have the significant potential to benefit from the implementation of EE & DR measures. However, there is lack of such a tool to estimate the potential of energy and demand savings of various EE & DR measures in refrigerated warehouses. In addition, it is difficult to quantify the impact of DR measures (e.g., turn off refrigeration system compressors) on the space temperature and the stored food quality that may limit the participation in demand response programs. Such a DR assessment tool for commercial buildings was developed by the DRRC research team in 2007 and received widely application in the field of demand response in buildings (Yin et al., 2010a and 2010b).

The purpose of this study was to develop a DR Quick Assessment Tool for Refrigerated Warehouses (DRQAT-RW) that can simulate DR events and their impact on the facility's electricity demand and space temperature. The results of this tool will help warehouse owners and operators to better position themselves for DR participation. In addition, the tool provides and evaluates recommendations about EE for individual refrigerated warehouses.

1.2 Problem Statement

Safety, food quality and demand reduction are customers' concerns during the DR participation. In particular, stored products such as fresh vegetables bring a challenge for customers to reduce the demand while maintaining product quality, because they are sensitive

to the temperature changes in the refrigerated warehouse. More generally, refrigerated facilities have acceptable range of temperature changes during a DR event. A tool that can be used by refrigerated warehouse owners and operators to quantify the impact of different DR strategies on the facility's load shed, space temperature, and food quality that can begin to address barriers to participation while also identifying associated cost benefits.

1.3 Research Methodology

In this study, we first reviewed EE and DR measures in refrigerated warehouses and identified EE and DR considerations for warehouse envelopes, refrigeration systems, and controls. Our primary focus is on the DR measures, including load shifting strategies (e.g., precooling) and load shedding strategies (e.g., increasing space temperature setpoint, lighting reduction).

EnergyPlus simulation engine was used to model the warehouse space. EnergyPlus is a whole building energy simulation program that models heating, cooling, lighting, ventilation and other energy flows in the building (DOE, 2015). Based on the summary of EE and DR measures, the modeling capabilities of refrigeration systems were identified in EnergyPlus.

The prototypical model of a refrigerated warehouse is comprised of a single-story warehouse with dock area, cooler, freezer and other refrigeration system zones. The model uses building geometry, envelope, internal loads, refrigeration systems, and operational schedules. Unlike the auto-sizing capability of the HVAC system in office buildings, refrigeration systems in refrigerated warehouses need to be customized based on the system temperature requirements and the amount of stored products. The key assumption in the model is that internal mass used to represent the stored product reflects the thermal inertia of the product rather than radiative interactions between the products and the warehouse envelope. The transportation of food products in the refrigerated warehouse is modeled as a heat gain at each time step by defining the heat gain density and schedule.

DRQAT-RW provides a relatively simple "wrapper" around a very complex building energy simulation program (EnergyPlus). It is designed specifically to calculate the energy and demand reduction potential under certain demand responsive strategies in Refrigerated Warehouses. In addition, the tool can also be used to evaluate the impact of control strategies on the stored food products in the refrigerated warehouse.

1.4 Key Findings

Development of DRQAT-RW, data collection from a cooler facility and verification of the tool's output resulted in several findings listed below:

- The measures of precooling, refrigeration system capacity limiting and battery charging management are very effective for load shifting in refrigerated facilities.
- The refrigeration system (compressors, condensers, and evaporators) is the single largest energy consumer at a refrigerated facility. Significant load shed can be achieved by complete refrigeration system shutdown during DR event hours.

- Cycling off air-handling units (AHUs) can provide fast demand response without impacts on the stored food.
- The control strategy of “Increase Space Temperature Setpoint” is effectively similar to shutting down the refrigeration system—the refrigeration compressors simply turn off (or reduce capacity if serving other refrigeration loads) until the space temperature rises to the new higher setpoint, at which time the compressors will turn back on.
- Demand Response Quick Assessment Tool for Refrigerated Warehouses (DRQAT-RW) can accurately estimate the effect of various EE and DR measures in a refrigerated warehouse.
- An analysis on the measured and simulated load demand and space temperature resulted in acceptable tolerance values suggesting that even without model calibration, DRQAT-RW is capable of predicting accurate space temperature and demand in refrigerated warehouses.
- The model’s predictions of refrigeration system demand show an acceptable agreement with the measured data (NMBE and CV(RMSE) for this comparison are 4.7% and 18.8%, respectively).
- The estimated demand reduction during a two hour DR test event was 157 kW and the maximum load shed achieved during an actual DR test was 126kW. The actual load shed was 20% lower compared to the DRQAT-RW estimate.
- This approach resulted in a better understanding of refrigerated warehouse operations, common practice and inventory traffic.

1.5 Report Organization

Chapter 1 introduces the topic and the scope of this report, research methodology and key findings. Chapter 2 discusses EE and DR considerations and strategies at refrigerated warehouses. Chapter 3 introduces the building modeling approach used for this simulation. Chapter 4 describes DRQAT-RW’s framework and modeling capabilities. Chapter 5 presents a case study that was used for validating the model and the tool’s output. Chapter 6 summarizes the conclusions and future work of this study.

CHAPTER 2: Energy Efficiency and Demand Response in Refrigerated Warehouses

This section features excerpts of the *Refrigerated Warehouse Demand Response Strategy Guide*, prepared by Lawrence Berkeley National Technology and VaCom Technologies (Draft, LBNL report pending publication). It addresses EE and DR strategies, and how they can be employed in various configurations of refrigerated warehouses, including the degree of control and automation required to properly implement them. It also highlights specific areas within refrigerated warehouses that are best suited to be targeted with the mentioned DR strategies.

2.1 Energy Efficiency Measures

Industrial refrigeration uses a significant amount of electricity year-round, and operating refrigeration plants efficiently has become increasingly important. Refrigerated warehouse owners and operators can choose to install or retrofit a system by making capital investments in new equipment, and/or by implementing control strategy improvements, to make their operation more efficient and to reduce operating costs. These EE measures improve efficiency either by reducing the required electric energy input for the refrigeration system, by helping to curtail the refrigeration load on the system, or by reducing both the load and the required energy input.

2.1.1 Envelope Measures¹

Envelope enhancements reduce the heat flux into the refrigerated space, either by decreasing the conductive heat transfer from the space surfaces or by reducing the infiltration air (and related convective heat transfer) through doorways into the refrigerated space. Common envelope EE measures are increased insulation and the use of infiltration barriers.

2.1.1.1 Increased Insulation

By increasing the amount of insulation in the walls, roof, and floor (for freezers) of the refrigerated space, heat flux into the space (and the resulting load on refrigeration equipment) is reduced. Furthermore, the benefit of higher insulation values is maximized when the temperature difference between the refrigerated space and the adjacent space is highest (which, in the case of exterior surfaces, typically occurs during the mid-afternoon, when DR events are most likely to be called).

2.1.1.2 Infiltration Barriers

Infiltration of relatively warmer air into a refrigerated space, either from the outdoors or from an adjacent space controlled at a higher temperature, is a primary contributor to temperature

¹ *Envelope measures* refers to elements related to the structure of the warehouse: walls, floor, inter-zonal partitions, doors, dock doors, insulation, etc.

rise in the space. Infiltration is often the cause of inefficiency in warehouses that have difficulty maintaining temperature, as it increases both the load and defrost requirements. A strategy for managing infiltration air is therefore considered essential in an overall approach to improving EE. Infiltration barrier types include, but are not limited to:

- Simple manual doors
- Strip curtains
- Automatic roll-up or bi-parting doors
- Air curtains

The effectiveness of each barrier type at reducing infiltration varies dramatically. However, infiltration barriers are selected based on a variety of criteria, including opening height (e.g., 14 ft. or higher for fork trucks for high-rise racking) or width, frequency of doorway passages, hours and the nature of the facility's operations, product type versus suitability of door closures, and other factors—not just infiltration effectiveness. In practice, infiltration can never be completely eliminated without severe consequences to warehouse productivity. Designers must balance their production requirements with the energy-saving benefits offered by each barrier type.

In general, “passive” barriers such as air curtains, which require no human intervention to close, are better than barriers that require human intervention to close. Often barriers such as a manual door or a roll-up door with a pull-cord closer, are simply left open.

2.1.2 Efficient Lighting and Lighting Controls

All lighting energy in a refrigerated space eventually becomes heat energy, which must be removed by the refrigeration system. Reducing lighting power therefore saves lighting energy as well as refrigeration system energy—for a standard freezer system operating at typical conditions, a watt of lighting power reduction would result in approximately 0.3 watts of compressor energy reduction.

T-8 and T-5 fluorescent lighting fixtures and light-emitting diode (LED) fixtures have replaced high intensity discharge (HID) light fixtures, such as metal halide and high pressure sodium lamps, in refrigerated spaces. An advantage of fluorescent fixtures over HID fixtures is that they have instant-start capability, meaning they can be controlled using motion or occupancy sensors. HID lamps take as much as 10 to 15 minutes to warm up before their lighting output reaches maximum levels, and while bi-level HID fixtures are available, power usage is still relatively high, even at the lower light level. An important consideration in refrigerated warehouses is that fluorescent fixtures in low temperature spaces typically can only be partially turned off, reducing power by one-half or two-thirds, depending on the fixture and ballast design.

Light-emitting diode lighting fixtures suitable for low-temperature applications are relatively new but are rapidly becoming the standard-practice lighting method for California refrigerated warehouses. LEDs offer even higher levels of EE over fluorescent fixtures. They have instant-

start capability, but unlike fluorescent fixtures can be turned completely off, providing greater savings with motion sensors. They also can be continuously dimmed, with some vendors providing communicating controllers, allowing fine-tuning of each fixture to optimize performance and savings.

2.1.3 System Measures

Refrigeration EE can be improved system wide by intelligently controlling the way the various interconnected components work together. The common system EE measures discussed in this section are lift reduction measures and mechanical subcooling.

2.1.3.1 Lift Reduction

The “lift” of a refrigeration system refers to the difference between the saturated condensing temperature (e.g., the head pressure, as pressure and temperature are equivalent for saturated fluids) and the saturated evaporating temperature. Reducing the magnitude of the lift, either by lowering the head pressure or by raising the evaporating temperature, increases the pumping capacity and EE of the compression stage.

2.1.3.2 Subcooling

Liquid refrigerant is said to be subcooled when its temperature is below the refrigerant saturation temperature at a given pressure condition. Subcooling requires a heat exchanger to cool the refrigerant at a constant pressure. The same thermodynamic benefit can be obtained by reducing the pressure of the refrigerant and removing the flash gas. Flash cooling is common in large industrial refrigeration systems, with refrigerant “cascaded” from higher to lower pressure vessels. Subcooling or flash cooling the refrigerant utilizes cooling capacity from a higher-temperature system (or the economizer port of a low temperature compressor) to cool liquid refrigerant from the condenser before going to the evaporator, which reduces the work of the low-temperature compressors. Since it allows some of the productive cooling to be performed at a higher suction pressure, subcooling or flash cooling improves overall system efficiency. In addition, subcooling can counteract liquid line pressure drop and variations in condensing temperature, facilitating reduced head pressure that in turn increases system capacity and efficiency.

2.1.4 Equipment Measures

Design, sizing, and operation of various equipment can affect a warehouse’s energy use significantly. This section discusses equipment-specific considerations that can help increase EE and reduce the facility’s load.

A large condenser can maintain the minimum saturated condensing temperatures (SCT) for more hours of the day than a smaller one can. Lowering the SCT reduces the compressor lift, which results in an overall increase in refrigeration system capacity and efficiency. Another way of saving energy in refrigerated warehouses is to eliminate the use of underfloor resistance heaters. A more energy efficient alternative to resistance heaters is to utilize the heat that is being rejected from the condenser through a heat exchanger. These EE measures improve efficiency either by reducing the required electric energy input for the refrigeration system (by

helping to curtail the refrigeration load on the system), or by reducing both the load and the required energy input.

2.2 Demand Response Considerations

Industrial refrigerated warehouses are excellent candidates for implementing DR. However, several different elements must be considered when gauging the feasibility of implementing a DR strategy. Those elements consist of facility, system, control, operational, and practical considerations. Table 1 presents the most important aspects of a refrigerated warehouse that must be considered if DR is to be implemented.

Table 1: Facility, system, control, and operational considerations for DR

DR Considerations		
Control	System	Facility
1. Evaporator Fan Speed	1. Condenser Sizing	1. Lighting
2. Compressor Part-Load Efficiency	2. Evaporator Coil Sizing and Selection	2. Infiltration
3. Defrost Considerations	3. Overall System Design	3. Underfloor Heating Systems
4. Space Temperature Variability		

2.2.1 Controls

Several control-related elements of a refrigerated warehouse must be considered when assessing the feasibility of implementing a DR strategy in that warehouse. This section will look at those elements.

2.2.1.1 Evaporator Fan Speed Control

All electric energy consumed by evaporator coil fans becomes heat load in the refrigerated space, not just the waste heat from fan inefficiency. Therefore, reducing fan energy is both a direct and indirect savings (seen as a reduction in compressor energy). For a standard freezer system operating at typical conditions, a watt of fan power reduction would result in approximately 0.3 watts of compressor energy reduction.

In addition, a variable-speed evaporator coil fan control provides an option to limit the coil fan speed during DR events, significantly reducing fan power while also maintaining a baseline level of air circulation and productive cooling in the space. The temperature rise during DR events may be limited, or possibly even completely mitigated, by allowing the fans to run at reduced speed. The fan speed can also be limited during the period after a DR event, to prevent all evaporator coil fan speeds from ramping to 100 percent speed at the same time, which could result in an acute spike in electric demand that may nullify the economic benefit of participating in the DR event in the first place.

2.2.1.2 Compressor Part-Load Efficiency

For screw compressors, variable-speed control (when implemented in conjunction with automatic compressor sequencing) improves the efficiency of the suction group when operating

at reduced capacity. For all compressor types, having one variable-speed machine in a suction group allows the group to continuously modulate capacity to match the time-variant suction load, resulting in more stable (and higher) suction pressure control.

Improved part-load suction group efficiency will result in higher demand shed for DR strategies where the refrigeration system is not completely shut off, such as in the following examples.

- If a capacity-limiting strategy is employed, where the refrigeration system is kept running during a DR event, either by reducing the evaporator coil fan speed or selectively shutting off some coils.
- For facilities where the refrigeration system serves a mix of long-term warehouse storage space and processing loads, where the process load cannot be curtailed during DR.

2.2.1.3 Defrost Considerations

Evaporator coil defrosts should be scheduled such that the DR event period, and the recovery period immediately afterwards, is avoided. Coil defrost periods reduce the refrigeration capacity that is available for space temperature pull-down. Every defrost cycle is a disruption to the cooling capacity in the space. During a defrost cycle, frost does not melt from the coil mass or fins until their surface temperature reaches 32°F. All defrost heat added to the coil mass to raise its temperature from the saturated evaporating temperature to 32°F, plus any additional heat that warms the coil above 32°F after all the frost has melted, must subsequently be removed by the refrigeration system after the defrost period has ended. Once the defrost temperature is attained, more moisture is driven off the evaporator in the form of water vapor. All of this moisture must be re-condensed on the evaporator coil, which requires refrigeration system capacity. If the coil defrosts during the recovery period after a DR event, the refrigeration system capacity used to recover from defrosting is consequently subtracted from the capacity available to recover the space temperature from DR.

Evaporator coils in spaces that are maintained above 32°F may partially defrost during DR events (if partial fan operation is employed for air circulation). In these spaces, the next scheduled defrost following a DR event is likely to require far less defrost time than a normal defrost, and in some cases might be completely avoidable. Demand defrost technologies are particularly useful in this instance. Freezer spaces are different; since the space is below the freezing temperature of water, ice and frost buildup on the coil before DR will persist on the coil through the duration of the event. It is important for the coils to be mostly defrosted before the DR event starts, so there is adequate capacity after the event for pulldown.

2.2.1.4 Space Temperature Variability

In general, the rate of temperature rise at any given point within a space is mostly uniform throughout the space when refrigeration is turned off, unless a significant source of heat (such as a doorway) is present. Since temperature rise is mostly uniform, it is important for the steady-state temperature in the space to also be uniform.

Good air circulation is essential for achieving uniform steady-state space temperatures. Warehouses where the evaporator coil throw direction is parallel to the pallet racking tend to have better overall air circulation throughout the space, which leads to more uniform space temperature during steady-state operation. Arranging the pallet racks and coils this way also avoids the possibility of stacking pallets in front of the air unit, which shortens air throw distance, disrupts air circulation, and contributes to non-uniform space temperatures.

2.2.2 Evaporator Coil Sizing and Selection

Evaporator coil sizing and selection has a big impact on a building's ability to participate in DR events. The evaporator coils' air flow volume should also be considered if DR capability is a design criterion. Care must be taken to select units that balance evaporator efficiency with air flow volume, which may be inversely related parameters. Evaporator coils with higher air flow circulate more air and can pull down the temperature of a refrigerated space faster than coils with low air flow.

2.2.3 Lighting Considerations

All lighting energy in a refrigerated space eventually becomes heat energy. Since the lights cannot be completely turned off without significantly affecting warehouse production, the lighting system represents a persistent load that, in the absence of any curtailment effort, can contribute to swings in space temperature when the refrigeration system is turned off during a DR event.

Fluorescent and LED lights are preferred over HID fixtures such as metal halide, high-pressure sodium, and mercury vapor lamps, for two primary reasons:

1. Fluorescent and LED lights are more efficient, meaning they radiate significantly less heat than HID fixtures (in addition to the self-evident advantage of consuming less electric energy and reducing demand).
2. HID fixtures take up to 10 minutes to ramp up from off to full brightness, and cannot be quickly switched off and on. HID lights are therefore not suitable for use with control devices, such as occupancy sensors.

Lighting energy is relatively simple to curtail during DR events. Assuming the light fixtures are fluorescent or LED, a portion of the lights can simply be turned off. For automatic DR, the lighting system can be networked to reduce demand based on an input from a programmable logic controller (PLC) or centralized control system, with no human intervention. Occupancy sensors are also an attractive control method, from both a DR and EE perspective.

2.2.4 Under-Floor Heater Considerations

In California, the current (2013 version) Title 24 EE standards (CEC, 2013) already require electric-resistance underfloor heaters to be shut off during all summer on-peak hours. The heaters should also be shut off during any hour of a DR event to avoid adding heat to the space when the refrigeration is off. For automatic DR, this means the heater controls must be

interfaced with the refrigeration control system or otherwise made capable of responding to a signal from the utility or DR aggregator.

Electric resistance heaters are safe and reliable but are not energy efficient. A more energy-efficient alternative is to use heat from the suction group discharge via a heat exchanger connected to a glycol loop that circulates glycol under the freezer slab. An even more efficient alternative is to actively subcool the refrigerant via a heat exchanger connected to a glycol loop.

2.2.5 Infiltration Considerations

Infiltration air, either from the outdoors or from adjacent spaces that are controlled to a higher temperature, contributes to as much as 80 percent of the load within a space. Infiltration air can also concentrate in “hot spots” of local warm air, diminishing the DR potential in the space, and jeopardizing product integrity. A strategy for managing infiltration air is therefore considered essential in an overall approach to implementing DR. To improve DR performance, it is suggested to install air curtains and another form of infiltration barrier, such as a roll-up door, for the passageway.

2.3 Demand Response Strategies

In general, DR strategies can be categorized as load-shifting strategies and load-shedding strategies. Load-shifting strategies move the load from one operational period to another, whereas load-shedding strategies avoid the load altogether. This section will cover the following strategies outlined in Table 2.

Table 2: DR strategies for refrigerated warehouses

DR Strategies	
Load Shifting	Load Shedding
<ol style="list-style-type: none"> 1. Precooling 2. Capacity Limiting 3. Battery Charger Load Management 	<ol style="list-style-type: none"> 1. Lighting Reduction 2. Demand Defrost and Defrost Termination 3. Infiltration Reduction Strategies 4. Turning Off Miscellaneous Equipment 5. Increasing Space Temperature Setpoints

2.3.1 Load-Shifting Measures

Load shifting is a process of redistributing energy use for refrigeration from on-peak or event hours, when demand and rates are highest, to off-peak hours, when rates are lower, by utilizing the thermal capacitance of the stored product. This section discusses three load-shifting strategies for refrigerated warehouses: precooling, limiting refrigeration system capacity, and battery charger load management.

2.3.1.1 Precooling

Precooling, or overcooling a refrigerated space, shifts a portion of the peak-day refrigeration load to the off-peak hours ahead of a DR or load-shift event. Precooling is an effective way to curtail the space temperature rise during a DR event when refrigeration is off. Precooling could increase the overall refrigeration system energy usage during a given DR event, because

evaporator coil fan speed has to increase during the precooling period to facilitate the overcooling. The resulting increase in evaporator coil fan energy outweighs the savings from increased compressor pumping efficiency at lower SCT from operating at cooler off-peak hours. On systems without evaporator fan speed control, the fan energy increase would not be a factor, and precooling would likely result in a slight net energy savings.

Frozen product storage spaces are good candidates for precooling; in general, because the product can often be cooled somewhat without affecting product quality. Cold storage spaces maintained around 30°F–35°F (1°C–2°C) present a unique challenge, since the goal in these spaces is often to maintain the product as cool as possible without freezing, which would damage the product. Thus, a precooling strategy in this temperature range is not feasible or is very limited. Higher-temperature spaces may often be cooled by a few degrees, although the product sensitivity must be considered. There are some products that are vulnerable to chilling injury, but can still tolerate lower temperatures for short durations without serious consequences. Other products are extremely sensitive to chilling injury and should never be overcooled. Examples of products that cannot tolerate overcooling include: cucumbers, cranberries, eggplant, melons, okra, pumpkins, squash, white potatoes, sweet potatoes, and tomatoes, among others (ASHRAE Refrigeration 21.1).

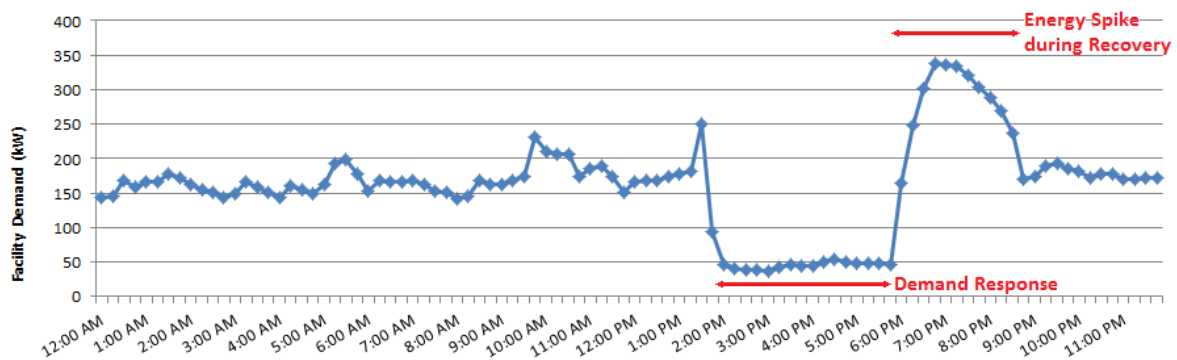
2.3.1.2 Limiting Refrigeration System Capacity

Limiting the capacity (and power) of refrigeration equipment, rather than turning it off outright during DR is an effective way to maintain a baseline level of productive cooling in a refrigerated warehouse, while also achieving reasonable load-shed goals in a DR strategy. Since refrigeration systems are designed to handle the peak load during the hottest part of the year, they are inherently oversized for the majority of the remaining operating hours of the year. The refrigeration system should therefore be as efficient as possible when operating at reduced capacity, to maximize yearly energy savings, and should especially be efficient at reduced capacity if a DR strategy that incorporates capacity-limiting is specified.

For refrigeration systems, capacity limiting should occur at the evaporator coils, either by limiting fan speed (or duty cycle for fan-cycling systems), or by turning off select units. Suction group and condenser capacity should be allowed to rebalance with the reduced load. Attempting to directly limit the capacity of the suction group could result in an increase in evaporating temperature in the lowest-temperature space served by the controlled suction group. Discharge air from the evaporator coils would accordingly increase, causing a relative heating effect in the space.

Capacity-limiting logic can also be employed during the recovery period following a DR event, when the refrigeration system equipment capacity modulates to reach full load. Figure 2 below shows the spike in demand at a refrigerated warehouse immediately following a DR event.

Figure 1: Spike in demand immediately following a DR event



For the example warehouse depicted in Figure 1, the spike in demand following the event nearly reached 350 kilowatts (kW), more than double the average daily demand of approximately 160 kW. For warehouses that are on energy tariffs that include high “facility” demand charges (e.g., non-coincident demand charges that apply to the peak monthly demand, regardless of which hour of the day they occur), the cost penalty resulting from setting a new peak demand is potentially significant.

A capacity-limiting control strategy can lessen the magnitude of the recovery period demand spike by spreading the recovery load across more hours. An example capacity-limiting strategy would be to limit the evaporator coil fan speed following the event for all evaporator coils with variable-speed control. The fan speed limit would be subject to a time delay, and each evaporator coil zone would be released to normal temperature-based speed control in a staggered sequence.

Capacity limiting during the recovery period is a strategy that requires fine-tuning to ensure that the space temperature can be fully pulled down before the following peak-day hours. Priority is always given to maintaining product integrity first, which may compete with the ability to manage the recovery demand spike if the system lacks adequate capacity to pull down the space temperature in fewer hours with reduced fan speed.

2.3.1.3 Battery Charger Load Management

Forklift and pallet lift battery chargers can be a large component of peak electrical load in refrigerated warehouses, and can also be a significant source of curtailment for DR. However, warehouse operation can limit this strategy. In warehouses with 24/7 operating schedule, forklift batteries need to be constantly charging to avoid any disruptions in the facility’s operation.

Field analysis showed that the savings potential from shifting battery charger load from peak hours to mid-peak ranged from 33–58 percent. Further savings would be possible for shifting battery charger demand to off-peak hours.

To successfully shift battery charger demand, a facility must have an adequate number of battery chargers and batteries available to pre-charge a reserve quantity of batteries for use during DR. There must also be enough units available to recharge the packs that were depleted during the DR event, in addition to the units available to handle the typical charging demand.

2.3.2 Load-Shedding Strategies

Load shedding is a process of avoiding energy use during on-peak hours altogether. Loads that are “shed” do not need to be “recovered” or made up for later.

2.3.2.1 Lighting Reduction

Lighting is a simple load to shed during DR events, since the lights can simply be turned off. Of course, production schedules and general safety will dictate the level to which lighting loads can be shed.

Networked LED lighting technologies exist to govern lighting system behavior at any level of granularity — across an entire facility, zone-by-zone, and all the way down to an individual fixture. The fixtures can operate based on a rule-based profile that takes input from occupancy sensors, ambient lighting conditions, and centralized control—which can be interfaced with automatic DR controls to respond to an event signal from a utility or an aggregator. Quick-starting fixtures such as T8 and T5 fluorescents and LED fixtures can alternatively be used in conjunction with occupancy sensors that dim (or completely shut off) fixtures when occupancy is not detected.

Regarding lighting curtailment, facility operators should also ask themselves: if a light fixture can be dimmed or shut off for DR, can it be shut off all of the time? Ideally, all non-necessary lighting should be turned off regardless of whether a DR event is in effect or not.

New for the 2014 California Title 24 building EE standards is a requirement that the total lighting power in buildings greater than 10,000 square feet need to be capable of reducing demand by at least 15 percent during DR events.

2.3.2.2 Demand Defrost and Defrost Termination

Defrost load can be shed through the use of technologies that initiate defrost cycles based on the level of frost buildup on the coil (e.g., demand defrost), rather than defrosting based on schedules or run-time accumulation. Temperature sensors on the coil surface can also be used to detect when the frost has been adequately melted from the surface, and terminate the defrost cycle accordingly (e.g., temperature-based defrost termination). These technologies avoid most of the excessive heat that is introduced into a space from scheduled, time-terminated coil defrosts.

2.3.2.3 Infiltration Reduction Strategies

Air infiltration into refrigerated spaces represents a significant heat source. During DR events, there may be opportunities to reduce infiltration air through inter-zonal doorways without severely affecting forklift traffic. Many facilities have adjacent spaces that have several

passageways between them, such as from loading docks to the adjacent refrigerated space. During a DR event, there may be opportunity to simply close a portion of the doors.

For facilities that utilize air curtains, a combination of air curtain and roll-up door could be used. The roll-up door would be kept open during normal operation, and closed during DR. The air curtain could then be shut off during the DR event. This strategy has the added benefit that the avoided power demand of the air curtain blower motor would contribute to the DR curtailment amount.

2.3.2.4 Turning Off Miscellaneous Equipment

Facilities with production equipment may have unique, site-specific opportunities to shed electric load by simply turning off equipment that is not in use during peak hours. Examples might include:

- Conveyor systems that are not used during peak hours
- Air compressors
- Blast freezers

2.3.2.5 Increase Space Temperature Setpoint

Increasing the space temperature setpoint is sometimes proposed as a method for load shedding during DR. This method is effectively similar to shutting down the refrigeration system—the refrigeration compressors simply turn off (or reduce capacity if serving other refrigeration loads) until the space temperature rises to the new higher setpoint, at which time the compressors will turn back on. The evaporator coil fans either remain on at 100 percent speed (if the facility lacks fan control), or reduce to minimum speed or duty cycle.

This method prioritizes space temperature control over participating in the DR event for any specific duration. The refrigeration system electric demand will return to normal levels when the compressors turn back on, which might occur before the end of the DR event is declared. Building operators should select a DR program that provides sufficient contract flexibility to avoid high penalties if the facility ends their participation should the refrigeration system turn back on before the event is over.

Successful implementation of this strategy requires an understanding of the unique air temperature profile in each of the refrigerated spaces, as well as the unique relationship of air temperature to product temperature in the individual spaces. A common warehouse design uses zone temperature sensors for evaporator coil control directly behind the coils, which presupposes that the average space temperature is equal to the average temperature of the air returning to the coil. This is a generally valid assumption for most spaces with good air circulation, and is accurate enough for evaporator coil and space temperature control. However, it likely does not accurately represent actual space air temperature when the air circulation is reduced, and certainly does not represent the product temperature. Moreover, the sensor reading provides no insight about the potential for localized hot spots within the space. If space temperature control is the top priority, then operators can consider allowing the fans to remain

on at reduced speed. This will keep some air circulating across the zone temperature sensor so that it is more representative of the actual space temperature (and provides air circulation in the space while avoiding high fan heat). Speeds as low as 30 to 40 percent can be used, which will greatly reduce fan power while still providing air movement in the room and across the temperature sensor.

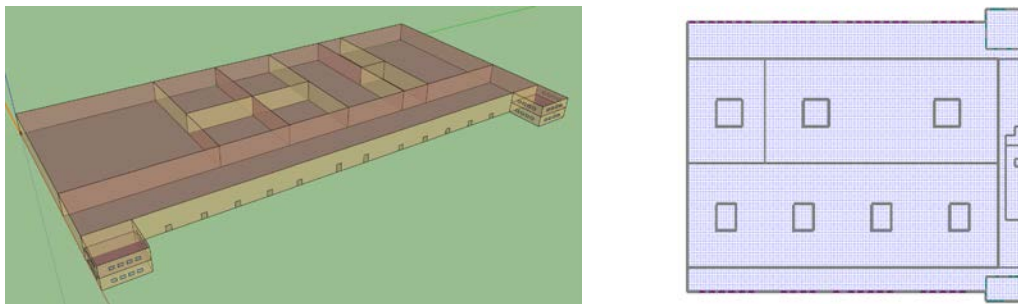
The review of various EE and DR measures in refrigerated warehouses provides the clear specification of modeling capabilities to be developed in the DR Quick Assessment Tool. Section 3 describes the approach used to develop a DR Quick Assessment Tool for Refrigerated Warehouses (DRQAT-RW). Concepts introduced in this section will later be used in determining DR strategies for modeled refrigerated warehouses.

CHAPTER 3: Refrigerated Warehouse Model Description

3.1 Building Model

The DRQAT-RW tool implements the reference refrigerated warehouse model in EnergyPlus and eQUEST (DOE-2, 2014), as shown in Figure 2. The prototype model of refrigerated warehouse in EnergyPlus was developed in a collaborate project between DOE, the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and Lawrence Berkeley National Laboratory (Deru et al., 2011). The prototype model in eQUEST was developed for use in codes and standards enhancement initiative in California (CEC, 2007). Both are used to assess the performance of various types of refrigeration system in the refrigerated warehouse.

Figure 2: Left, Reference Refrigerated Warehouse Model in EnergyPlus (EnergyPlus, 2014) Right, DOE-2 Model of Refrigerated Warehouse (eQUEST, 2014)



Both in the EnergyPlus and eQUEST prototype models, office, dock area, cooler, freezer and sub-freezer are defined based on each zone's functionality, type of stored food product and refrigeration system temperature setpoints. Based on these precedents, we defined refrigeration system zones in the DRQAT-RW backend model as presented in Table 3.

3.1.1 Geometry

The reference refrigerated warehouse model contains a number of zones, which can be categorized into several types based on its functional and operational characteristics. As shown in the three-dimensional model (Figure 3), the storage and dock area is one story, while the office area is two stories. Stored goods go through the dock area before going into the freezer/cooler area.

Each zone has a different thermostat level to preserve specific foods. The freezer and cooler spaces implement a dual-thermostat control strategy, while the dock and office spaces implement a single-thermostat control strategy. The thermostat level and stored content for each zone type are summarized in Table 3.

Table 3: Refrigerated Zones' Temperature Setpoints and Stored Food

Zone Types	Thermostats	Contents Stored
Blast Freezer	-27°C~-25°C (-17°F~-13°F)	<input type="checkbox"/> Fish frozen <input type="checkbox"/> Meat frozen <input type="checkbox"/> Fruit frozen <input type="checkbox"/> Vegetable frozen <input type="checkbox"/> Ice cream <input type="checkbox"/> Others
Freezer	-18°C~-20°C (-4°F~4°F)	<input type="checkbox"/> Fish frozen <input type="checkbox"/> Meat frozen <input type="checkbox"/> Fruit frozen <input type="checkbox"/> Vegetable frozen <input type="checkbox"/> Ice cream <input type="checkbox"/> Others
Cooler	2~4°C (36°F~39°F)	<input type="checkbox"/> Fruit Fresh <input type="checkbox"/> Vegetables Fresh <input type="checkbox"/> Daily milk <input type="checkbox"/> Others
Dock	10°C (50°F)	
Office	20°C (68°F)	

3.1.2 Building Construction Configuration

The construction configurations summarized in Table 4 and Table 5 below satisfy the code requirements in the California Title 24 building EE standard. The R-value is a measure of thermal resistance used in the building and construction industry, which is the reciprocal of the U-value. Typically, ceiling, wall and floor constructions for large facilities are built to achieve R-values from R-31 to R-50, R-32 to R56 and R-18 to R30, separately. The default R-values in the DRQAT-RW prototype model are given in Table 4. As presented in Table 5, the wall separating a cooler from a freezer typically has the R-value of R-36 for insulation. These walls are typically built to a higher R-value than the suggested code minimum of R-26.

Table 4: Summary of the Construction Configuration for Warehouse Envelopes

Zone Types	Exterior walls	Floor Construction	Roof Construction
Freezer	R36	R36	R36
Blast freezer	R36	R36	R36
Cooler	R28	R28	R28
Dock	R25	R25	R25

Table 5: Summary of Interior Walls for Each Refrigerated Zones

Zone Types	Interior walls
Freezer to Freezer	R36
Blast Freezer to Freezer	R36
Freezer to Cooler	R36
Cooler to Cooler	R28
Freezer to Dock	R36

There does not appear to be any variability in construction or insulation performance in refrigerated warehouses, which is different from the building shell requirement for commercial buildings in California.

3.2 Stored Food as Internal Mass

Compared with other commercial building types, refrigerated warehouses usually store a large quantity of contents. They may present significant thermal inertia and thus need to be well handled in the energy modeling. In EnergyPlus, they are represented by Internal Mass, which takes into account the convective heat transfer between the contents and the indoor air but does not account for the radiative interactions between the contents and the warehouse shell. Because of the large amount of internal mass, the simulated building warm-up usually requires a longer time than that in the simulations for other commercial building types.

Three modeling objects (i.e., Internal Mass, Construction, and Material) are used in the model to describe the physical and thermal properties of the stored goods, including density, conductivity, specific heat, surface area, and other parameters. Default values are provided in the model for common refrigerated warehouse contents, such as frozen fish and vegetables.

3.3 Refrigeration Systems and Operations

The reference model implements direct expansion (DX) air chillers with banks of compressors to provide refrigeration. Unit heaters are used to maintain temperatures during the winter for the cooler and dock areas. A number of refrigeration air coils are modeled to allow for diversified defrost schedules. This diversity, along with the internal mass, is necessary to maintain the desired temperature control.

The Air-Chiller object of Refrigeration System in EnergyPlus is used in the model to simulate the performance of the air chiller. It works in conjunction with a refrigeration chiller set and a refrigeration system. The air chiller model uses information at rated operational conditions along with the zone conditions to determine the actual chiller performance. Energy use for fans and heaters is modeled based on inputs for nominal power, schedules, and control type. The refrigeration chiller model accounts for the sensible and latent heat exchange with the surrounding environment (EnergyPlus, 2014).

The above-mentioned model objects are designed to collect comprehensive information to accurately describe the refrigeration system performance. Default values can be used when some information cannot be obtained by the user.

Refrigeration load is highly dependent upon the warehouse operating conditions. Therefore, the building model requires extensive operation information for the accurate energy simulation, including:

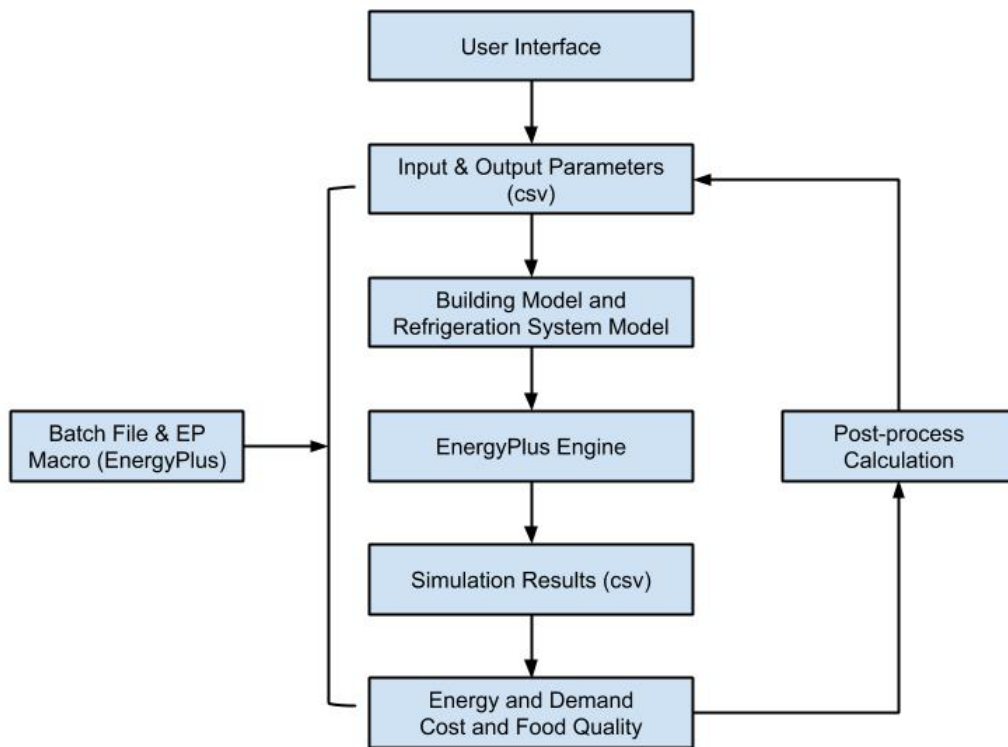
- Air mixing via doors between different zones
- Infiltration conditions
- Occupant conditions
- Lighting conditions
- Internal equipment conditions

CHAPTER 4: DRQAT-RW Framework and Modeling Capabilities

4.1 Tool Structure

Figure 3 shows a high-level schematic framework of the DRQAT-RW tool and the data structure of the back-end model and front-end user interface. The MS-DOS batch file and EP Macro in EnergyPlus are used to exchange the input and output parameters between user input on the front interface and the backend EnergyPlus simulation model. A post-process model was also developed to calculate the energy and demand savings and the impacts of EE and DR measures on the system performance and food quality.

Figure 3: Schematic Framework of DRQAT-RW



4.1.1 MS-DOS

The MS-DOS programs in DRQAT-RW are designed for constructing the building model using the model input Macro feature and obtaining simulation results using EnergyPlus. The key to the DOS programs is that they create a building model according to the data input by users. The DOS program reads the user input and translates it into an EnergyPlus file (.idf). This program then calls EnergyPlus and runs this file. Finally, there is a post-process program to calculate the energy cost, energy cost savings, and other output data.

4.1.2 Input Macros

The Input Macros feature increases the flexibility of the EnergyPlus input file. For the building model in DRQAT-RW, users simulate a building model with a specific climate zone, building geometry, internal load, occupancy pattern, operating schedule, and HVAC system characteristics. Input macros would be the input values of these variable parameters.

The basic capabilities are:

- Incorporating external files containing pieces of the IDF (EnergyPlus input files) into the main EnergyPlus input stream.
- Selectively accepting or skipping portions of the input.
- Defining a block of input with parameters and later referencing this block.
- Performing arithmetic and logical operations on the input.
- Input macro debugging and listing control.

These capabilities are invoked in the EP-Macro program by using macro commands. Macro commands are preceded by ## to distinguish them from regular EnergyPlus input commands. After execution by the EP-Macro processor, macro commands produce regular lines of EnergyPlus input that are shown in the resulting IDF file (out.idf) and, subsequently, in the EnergyPlus echo print (audit.out). Descriptions of input macros are given at the end of this section; they should be reviewed before reading the macro command description.

The EP-Macro allows users and developers to change the input parameters of the building model, such as building geometry, building location, building operation, and so on. A block input with parameters is defined first, and then an AWK programming language is used to read the value of these parameters from input files. External files are then incorporated into the main EnergyPlus input file.

4.1.3 Tool Interface

Delphi is a high-level, compiled, strongly typed language that supports structure and object-oriented design. Based on Object Pascal, its benefits include easy-to-read code, quick compilation, and the use of multiple unit files for modular programming. Delphi has special features that support Code Gear's component framework and Rapid Application Development (RAD) environment. Therefore Delphi could make a function-strong, friendly interface that meets the requirements of DRQAT-RW.

The purpose of using Delphi is to achieve the data transfer between the interface and the main DOS batch file. The interface made by using Delphi is user-friendly, so users could easily evaluate energy consumption, demand reduction, and cost savings for individual buildings when applying different DR strategies to the building.

Figure 4 is the main interface of the refrigerated warehouse model inputs in DRQAT-RW designed by Delphi. Base on the user's inputs of his/her facilities, the tool will generate a model for simulating user defined EE & DR measures' effect on the energy and demand performance.

Figure 4: Interface of Refrigerated Warehouse Inputs in DRQAT-RW

Project & Site & Geometry		
Location		
Zip Code	94063	
City	REDWOOD CITY	

Building Information	
Building Type	Refrigeration Warehouse
Building Name	Building
Built Year	Title-24 2008
Construction	Advanced User Input

Building Geometry			
Story	1	Floor Height	45 ft
Length	656 ft	Width	210 ft

Refrigerated Zones			
Zone1	Cooler	100	% of Total Floor Area
Zone2	Freezer	0	% of Total Floor Area
Zone3	Blast Freezer	0	% of Total Floor Area
Zone4	Dock	0	% of Total Floor Area

4.2 Modeling of the Stored Contents in RW using EnergyPlus

4.2.1 Challenges of the EnergyPlus Modeling for Stored Contents in RW

The thermal response properties of buildings are at the heart of the management of building energy systems. Compared with other commercial building types, refrigerated warehouses usually store a large quantity of goods that can be considered as internal thermal mass. The massive goods usually present a significant thermal storage effect, which further changes the building thermal response properties. More specifically, excitations from the surrounding environment and HVAC equipment usually take a longer time to cause changes in the indoor environment. Such thermal inertia is highly related with the DR strategy design, and therefore needs to be well addressed in the building energy modeling (Zhang et al. 2014).

Moreover, the type and amount of the stored goods may vary at different times; in other words, the thermal properties and amount of internal mass are dynamic, rather than constant. This brings extra challenges for modeling refrigerated warehouses. Due to the changes in inventory, the building model itself needs to be updated dynamically to represent the variations of the internal mass settings. This cannot be well handled by the existing internal mass objects within EnergyPlus, which assumes constant thermal properties and amounts for the internal mass.

4.2.2 Development of the modeling approach using Energy Management System

To address the modeling challenges discussed above, a new modeling approach has been designed using the Energy Management System (EMS) feature within EnergyPlus. EMS is an advanced feature of EnergyPlus that allows the development of customized supervisory control to override selected aspects of EnergyPlus modeling.

In this study, EMS is used to update the building model by overwriting the thermal properties and amount of internal mass dynamically, implementing a special feature named *construction state actuator*, which was originally designed to model dynamic technologies of thermal envelopes. More specifically, an actuator is created for every internal mass object in the selected zones. It is used in conjunction with the input object “ConstructionIndexVariable” of the EMS component in EnergyPlus, which refers to several different construction objects representing the variations of the amounts and types of the stored goods. The input object creates and fills a global ERL variable with the value that points to a specific construction, and then the variable is assigned to the construction state actuator to override the original construction state of the thermal mass. In this way, the building model can be updated at different time steps (DOE, 2013).

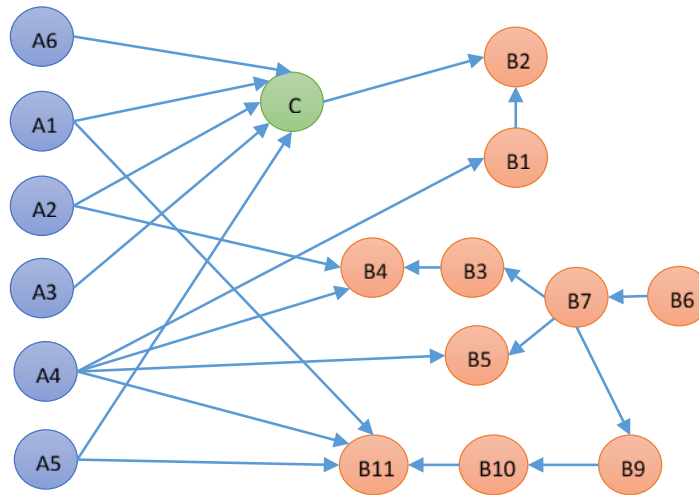
4.2.3 Description of the modeling approach

In general, there are two types of effects caused by the addition/removal of stored goods, and they are modeled separately:

1. **Effect (1): Additional heat gains when goods with a higher initial temperature are moved into warehouse.** This effect is modeled by creating an extra internal gain object, with the transient heat transfer values calculated by an auxiliary pre-process program. During the heat transfer analysis, it is assumed that the stored goods are solid objects with constant cross-sectional area, and the goods moved into the warehouse have a uniform temperature distribution that is specified from the user input.
2. **Effect (2): The variations of the amount and properties of the internal thermal mass.** This effect is modeled by changing the internal mass properties using EMS objects. More specifically, a new construction representing the reduced internal mass is created first, and the corresponding construction is assigned to the internal mass by EnergyManagementSystem: Actuator, following the indicator defined in EnergyManagementSystem: Sensor. It is assumed that the addition/removal of the stored foods in a specific zone follows a daily schedule, i.e., the goods are moved out at the same time every day and the same amount of goods are moved back later that day.

Figure 5 shows a schematic chart for the modeling approach, illustrating the relationships between the user input information and the corresponding EnergyPlus modeling objects.

Figure 5: Schematic chart for the EnergyPlus modeling of stored contents in RW



Note:

A: User input information describing the food storage and transportation

B: EnergyPlus objects modelling the food storage and transportation

C: Pre-process program analyzing the transient heat transfer from moved-in goods

Input information that is necessary for the modeling include the following:

- A1: Amount of the stored contents added/removed
- A2: Time for the stored contents to be moved in/out
- A3: Temperature of the stored contents when moved in
- A4: Name of the Zone with stored contents addition/removal
- A5: Properties of the stored contents (default: same as the ones in the reference model)
- A6: Indoor airflow velocity of the specified zone (for the heat transfer analysis)

Based on the given information, the approach generates a number of EnergyPlus objects modeling the stored contents, including the following:

- B1: OtherEquipment, e.g., InternalGains_Freezer_1
- B2: Schedule:Compact, e.g., Schedule_HeatRelease_Freezer_1
- B3: EnergyManagementSystem:Sensor, e.g., Freezer_1_Load_sensor
- B4: Schedule:Compact, e.g., Freezer_1_Load_schedule
- B5: EnergyManagementSystem:Actuator, e.g., Freezer_1_Load_actuator
- B6: EnergyManagementSystem:ProgramCallingManager, e.g., Freezer_1_Load_manager
- B7: EnergyManagementSystem:Program, e.g., Freezer_1_Load_control
- B8: Output:EnergyManagementSystem
- B9: EnergyManagementSystem:ConstructionIndexVariable, e.g., Freezer_1_Load_low
- B10: Construction, e.g., Freezer_1_Load_low_construction
- B11: Material, e.g., Freezer_1_Load_low_material

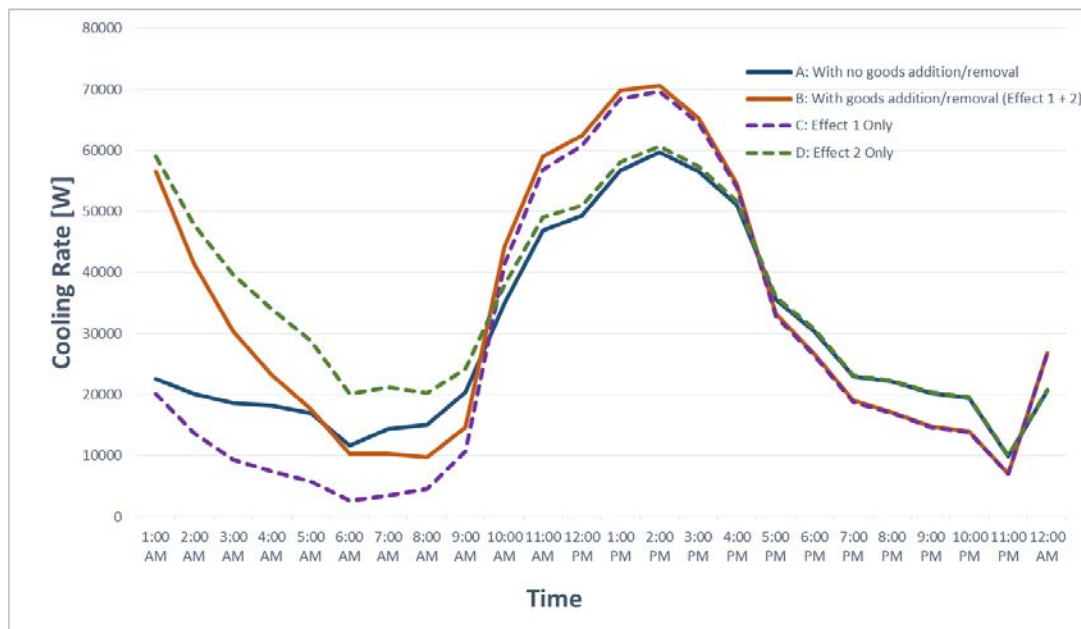
4.2.4 Case Study of Food Transportation

The following four cases are modeled and simulated in EnergyPlus, in order to investigate the effects of stored goods addition/removal on the zonal cooling load:

- Case A: With no goods addition/removal
- Case B: With goods addition/removal (Effect 1 + 2)
- Case C: Effect 1 only (extra heat gains, but no thermal mass variations)
- Case D: Effect 2 only (goods are moved in with the same temperature as indoor air)

Case A and B are used to model the real cases with and without goods addition/removal. Case C and D are virtual cases created to investigate the individual influence from Effect 1 and Effect 2, respectively. In Case B and D, it is assumed that 20% of the stored goods (frozen fish) in the freezer located in the upper left corner are moved out at 8:00am every day, and then the same amount of goods are moved back into the freezer at 12:00am with a uniform temperature distribution of 4 °C. In Case C, the heat gains that are equivalent to the heat transfer from the moved-in goods in Case B, but the internal thermal mass are kept constant. Figure 6 summarizes these results of product traffic's effect on the RW cooling rate.

Figure 6: Effect of product traffic in/out of the RW on cooling rate (Source: EnergyPlus)



The above figure shows the cooling rate profiles for a typical day in the four cases. It can be observed that the profiles B and A present remarkable differences through the whole day, illustrating the total effect caused by the goods addition/removal. Profile D presents higher values than A in the first several hours after the addition of goods (12:00am~9:00am), and then becomes similar to A. This means that the effect caused by the temperature difference between the moved-in goods and indoor air gradually decreases, and can be ignored after about 9 hours.

Case D and Case A have a different thermal inertia due to the variations of the internal mass, and thus lead to different profiles through the day.

4.3 Default Inputs of DRQAT-RW (ASHRAE Handbook and Title-24 Code)

The tool comes preloaded with some default values to help users in case some of the parameters are not known. These default values are mainly characterized into the following groups: (1) building shell; (2) space loads (people, lighting, plug loads and infiltration); (3) refrigeration systems and (4) operational schedules, as summarized in Table 6.

Table 6: Prototype Refrigerated Warehouse Model Description (PG&E, 2007)

Model Parameter	Default Input Value
Shape	Rectangular (656 ft by 210 ft)
Number of floors	1
Floor to ceiling height	45 ft
Exterior wall R-value	R36 (Freezer) R28 (Cooler) R25 (Dock)
Interior wall R-value	R36 (Freezer to Freezer; Freezer to Cooler; Freezer to Dock; Cooler to Dock) R28 (Cooler to Cooler)
Roof R-value	R36 (Freezer) R28 (Cooler) R25 (Dock)
Lighting power density	0.6 W/ft ²
Plug power density	0.7 W/ft ² (fork lifts, miscellaneous plug loads)
Infiltration	Cooler and Freezer: 0.1 ACH (air changes per hour) Loading Dock: 0.3 ACH
Operating schedule	24/7
Zone temperature setpoints	Freezer: 0°F Sub-freezer: -13°F Cooler: 40°F Dock: 50°F Office: 70°F
Condenser type	Air-cooled, linear fan speed control
Condenser fan power	0.15 W/CFM (0.32 hp per ton)
Condenser fan and pump power	330 Btu/watt
Evaporator type	Constant volume, continuous fan operation
Evaporator size (climate zone 13)	Cooler: 392 ft ² /ton Freezer: 295 ft ² /ton Dock: 218 ft ² /ton
Evaporator size (climate zone 13)	Cooler: 4.3 cfm/ft ² Freezer: 4.8 cfm/ft ² Dock: 7.9 cfm/ft ²

4.4 Model Capabilities of EE and DR using DRQAT-RW

The tool development of DRQAT-RW bridges the gaps in current modeling capabilities of refrigeration system performance, and to expand our existing tool of DRQAT for large commercial office buildings. Based on the summary of EE and DR measures in refrigerated warehouses in the section 2, a set of model parameters has been defined in the backend EnergyPlus model, which will enable simulation users to modify those parameters to assess the impacts of EE and DR measures on whole-building energy use and operation in a fast and easy manner.

The primary goal of using DRQAT-RW is to evaluate the impact of DR control strategies on the whole peak demand and refrigeration system zone temperature changes. In addition, the tool of DRQAT-RW can still be used to analyze the effect of EE measures in refrigerated warehouses for reducing whole building energy use. Modeling capabilities of EE and DR measures in refrigerated warehouses are listed as follows.

Table 7: Modeling Capabilities of EE Measures in Refrigerated Warehouses

Category	EE Measures	DR Measures
Building shell	<ul style="list-style-type: none"> • Increase R-values of building shell • Improve infiltration barriers to reduce air change rates 	None
Space load	<ul style="list-style-type: none"> • Improve lighting and plug loads efficiency 	<ul style="list-style-type: none"> • Dimming or turn off lights • Turn off Miscellaneous Equipment
Evaporator and condenser systems	<ul style="list-style-type: none"> • VFDs on evaporator and condenser fans • Improve fan efficiency on evaporator and condenser fans • Limits on air-cooled condenser drybulb approach temperature • Limits on evaporative condenser approach temperature • Reduce the saturated condensing temperatures 	During the peak hours: <ul style="list-style-type: none"> • Precooling system zones before the peak hours • Increase system zone temperature setpoints • Turn off evaporators • Turn off entire refrigeration systems in freezer zones
Compressor	<ul style="list-style-type: none"> • VFDs on compressors 	<ul style="list-style-type: none"> • Turn off compressors in cold storage

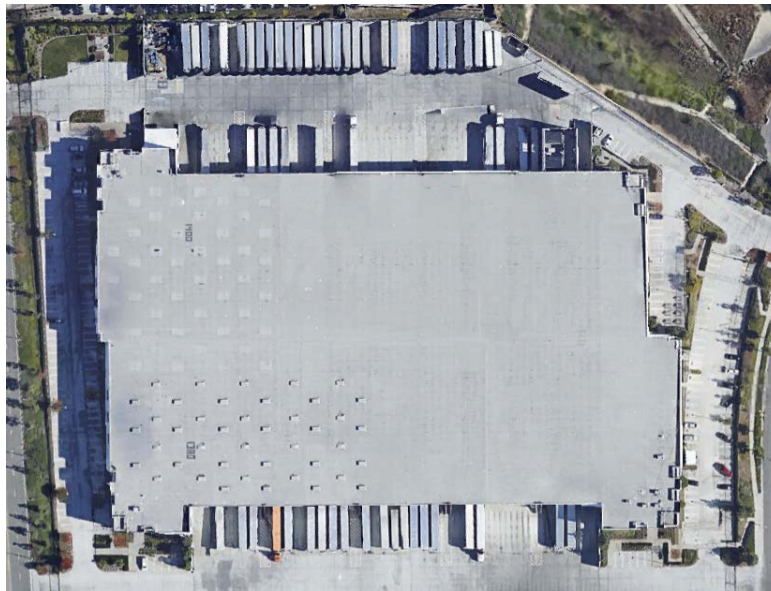
CHAPTER 5: Case Studies of Model Validation

This section summarizes the information gathered to study a cooler facility in Southern California (CA climate zone 6). First, we collected information during a site visit. The collected information included facility type, refrigeration system specifications, common practices at the facility, and previous experience with DR events. Second, we developed the model using DRQAT-RW and validated the model by comparing the measured data with the simulated results. Finally, the calibrated model was used to predict DR performance of a certain control strategy and assess the load shed potential during the peak hours at the site.

5.1 Refrigeration Warehouse Site Visit

In order to better understand the operations of a refrigerated warehouse and develop a more user friendly tool, the team at LBNL visited an actual cooler facility shown in Figure 7. The warehouse has a rectangular geometry of 656 ft by 210 ft. Information collected during the site visit, from the facility's Human Machine Interface (HMI), and data collected from temperature probes were used to test the DRQAT-RW model.

Figure 7: Aerial View of the Refrigerated Warehouse (Source: Google Earth)



5.1.1 Facility Types and Refrigeration Systems

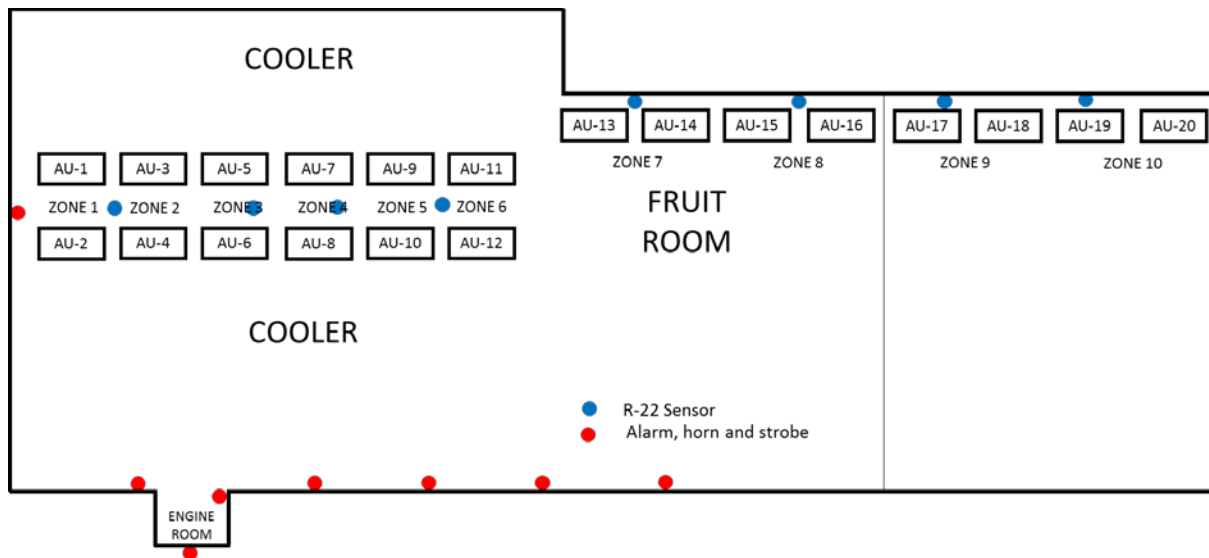
Table 8 summarizes facility's key attributes as well as the refrigeration system type and size. Figure 8 shows the layout of the facility, different zones, and location of air handlers. There are 10 zones and 20 air handlers (evaporators) throughout the facility. Refrigeration system's compressor and condenser are located in the engine room. The information specific to the cooler facility used in this study has been anonymized for privacy concerns.

Table 8: Summary of Refrigeration Warehouse

Facility Name	Year Built	Floor Area	Cooler Setpoints	Schedule	Product Traffic	EE and DR Measures
Cooler Facility	2003	137,126 ft ²	35°F	24/7/365	Large quantities of Dairy and Fruit products are transferred every month	Floating Head Pressure with variable setpoint, variable speed. Min SCT: 70°F Variable Speed on Air Units Floating Suction Pressure Evaporator Defrost Automation

Figure 8 shows the schematics of this warehouse facility. Air-handling unit 1~12, 13~16 are located in the cooler space and the fruit room, respectively.

Figure 8: General Mills Refrigerated Warehouse Layout



The facility was built in 2003 and has only cooler space (38°F–39°F) for fresh fruit and yogurt storage. The incoming product is 5°F colder than the warehouse setpoint. The product usually comes in at 33°F–34°F, whereas the warehouse’s air temperature is typically 38°F. The refrigeration system is made up of a single-stage R-22 system with thermo-syphon oil cooling and evaporative condensing. There are three compressors at the facility’s engine room. There are three condensers in the engine room. There are two condensers at the facility, with two fans serving each condenser. All four fans have variable frequency drives. The facility uses high-pressure gas defrost and not electric defrost. Detailed refrigeration system specifications are listed in Table 9 and Table 10.

Table 9: Equipment Summary of Compressor, Condenser, and Evaporator Systems

Compressor	Quantity	4	
	Type	Screw	
	Make	Frick	
	Model	RWFII-100	
	HP	200	
	Performance Characteristics at Design Conditions	222.3 TR / 204.4 BHP	
Condenser	Quantity	2	
	Type	Evaporative	
	Make	Evapco	
	Model	PMCB 815	
	Pump HP	7.5	
	Fan 1 HP	25	
	Fan 2 HP	15	
Performance Characteristics at Design Conditions	12,226 MBH @ 100°F SCT & 70°F WBT		
Evaporator	Quantity	4	12
	Make	Evapco	Evapco
	Model	NTCA2L 66103-750M4	NTCA3L 9983-10M4
	Fans per Unit	1	1
	Fan HP	7.5	10
	Performance Characteristics at Design Conditions	22.3 TR at 10°F TD	

Table 10: Lighting information of Refrigeration Warehouse

Lighting Information	Type of Bulb	T8
	# of Fixtures	174
	Watts per Fixture	272
	Total Watts	47328

There are no roll-up doors, but some docking ports are insulated and reduce air infiltration during loading and unloading. During normal operations the door activity is not monitored and there is significant air mixing between the unrefrigerated forklift battery charging room and the cooler area.

5.1.2 Demand Response at the facility

The facility already takes part in DR events. Since it is only a cooler facility, the DR events are shorter (2–4 hours) than they are in a typical freezer space (~6 hours). In a cooler, product temperature is more important, as the variation band is much smaller. In a freezer, even with the rise of ambient air temperature, the frozen product temperature will remain constant for a longer time.

During a DR event, the operator instructs personnel to be more aware about door opening and closing, since the facility has no automatic roll-up doors. Turning the lights off is not part of the facility's DR strategy, as it is considered to be a safety hazard. Forklift chargers are also not turned off during DR events since the facility's 24/7 operating schedule requires constant charging of forklift batteries. The office space of the facility also takes part in DR events, where HVAC system and unnecessary lights are turned off. All offices and common areas outside of the cooler are equipped with occupancy sensors.

The facility participates in two different DR events:

- Total facility shutdown, in which the entire refrigeration system is turned off.
- Fly wheeling, where the air handlers for every other zone are turned off and compressor capacity is reduced. The refrigeration continues, but at a lower capacity which results in reduced demand.

Major concerns for facility manager when DR events are called are the following:

- Door management
- Product temperature before DR (not warehouse air temperature)
- Refrigeration liquid level during normal operations.

5.1.3 Case Study Data Collection

The refrigerated warehouse uses VaCom's EnergyDashboard® refrigeration performance software to collect and analyze refrigeration system data. Refrigerated space temperature data was collected and analyzed using ten different probes in variety of spatial locations. Refrigeration system equipment were monitored using the facility's HMI and their load data was recorded using the EnergyDashboard®. Data was collected for a six week period with one minute resolution. The following data points were collected during this case study:

- Space temperatures
- Refrigeration system control setpoints
- Individual component run times
- Operating temperatures and pressures
- Capacity
- Electric demand

The temperature data was collected at up to ten individual locations within the refrigerated space, with locations selected to "map" the three-dimensional temperature profile of the

refrigerated space. Wireless temperature sensors, receivers, and data acquisition modules from VaCom’s instrumentation library were used for this task.

To the extent possible, the following information was collected about product throughput, holding volume, and product temperature during the six week data collection period. Where available, the following information was collected:

- Mix of product stored at any time during the monitoring process.
- The volume/mass of product stored at any time during the monitoring period, and information about product traffic entering and leaving the warehouse over the course of the monitoring period.
- The entering product temperature during the duration of the test period, if this information is collected regularly.

During the six-week data collection period, two DR events were simulated at the refrigerated warehouses with pre-cooling prior to the test. The simulated events were initiated remotely by VaCom, and space temperatures were monitored remotely throughout the event to ensure space temperature remains within acceptable limits.

The simulated events are expected to show an accurate representation of the facility’s electricity demand and space temperature during an actual DR event. However, since the simulated events took place during the winter when ambient temperatures (and refrigeration system demand) are low, the actual magnitude of the load shed is expected to be lower than a hot summer day DR event.

5.2 Model Development using DRQAT-RW

As summarized in the previous section, all the necessary data for running a warehouse simulation was collected either through VaCom Technologies or the facility operator and HMI during the warehouse visit. This information was then used to build a model of this refrigerated warehouse in DRQAT-RW and simulate a DR event. The results of this simulation were then compared side by side to verify the tool’s results, calibrate a model and provide an example for potential users.

5.2.1 Model Inputs from Site Data Collection

Table 11 summarizes the basic inputs required for running DRQAT-RW. For information regarding the input parameters, their definitions and default values refer to the user manual drafted for this tool “DRQAT-RW-V-1-0-0: User’s Manual”.

Table 11: Basic Required Inputs for DRQAT-RW

Facility Type	Refrigerated Warehouse - Cooler	
Location	CA Climate Zone 08 (Reference City: Los Angeles)	
Year Constructed	2003	
Floor area	Total: 137,126ft ²	
Number of floors	1	
Geometry	Length	656ft
	Width	210ft
Facility operational schedule	24/7/365	
Utility Rate Input		
Electricity	SCE-TOU-GS-3	
Warehouse Zone Input		
Internal Loads	Number of People	10
	Lighting	0.34W/ft ²
	Equipment	0.28W/ft ²
	Infiltration	0.25ACH
Stored Product	Fresh Fruit	
	Processed Dairy	
	Mass weight	3,539,727lbs
	Storage Temp	38~39°F
Refrigeration System Input		
Compressor	Quantity	3 (only one was running during the site visit)
	Power Input	150,000W
Condenser	Condense Type	Air-Cooled
	Fan Speed Control	Fixed Linear
	Rated Fan Power	15,000W
	Minimum Fan Airflow Ratio	0.25
Evaporator (Air Chiller)	Quantity	6
	Cooling Capacity	20,200W
	Fan Power	5,595W
	Defrost Type	Hot Fluid
Refrigeration System Operations	24/7/365	
Simulation Running Period	2/12/2015~2/18/2015	

5.2.2 Results Analysis (Simulated vs. Measured)

For the model validation of this study, several standards and guidelines (ASHRAE, 2002) provide the acceptable calibration tolerance of the cumulative variation of root mean squared

error (CVRMSE) and the mean bias error (MBE) for annual, monthly, and hourly data calibration. A simulation model can thus be calibrated until it satisfies all of these criteria. Here are definitions of each metric used in the following equation: M (Measured), S (Simulated), and N (Number of month). The hourly metrics are calculated based on the same equations as follows.

$$\begin{aligned}
 \text{MBE}_{\text{month}} (\%) &= \left[\frac{(M-S)_{\text{month}}}{M_{\text{month}}} \right] \times 100\% \\
 \text{CV}(\text{RMSE}_{\text{month}}) (\%) &= \left[\frac{\text{RMSE}_{\text{month}}}{\overline{M}_{\text{month}}} \right] \times 100\% \\
 \text{RMSE}_{\text{month}} &= \left\{ \frac{\left[\sum_{\text{month}} (M-S)_{\text{month}}^2 \right]}{N_{\text{month}}} \right\}^{1/2} \\
 \overline{M}_{\text{month}} &= \frac{\sum (M_{\text{month}})}{N_{\text{month}}}
 \end{aligned}$$

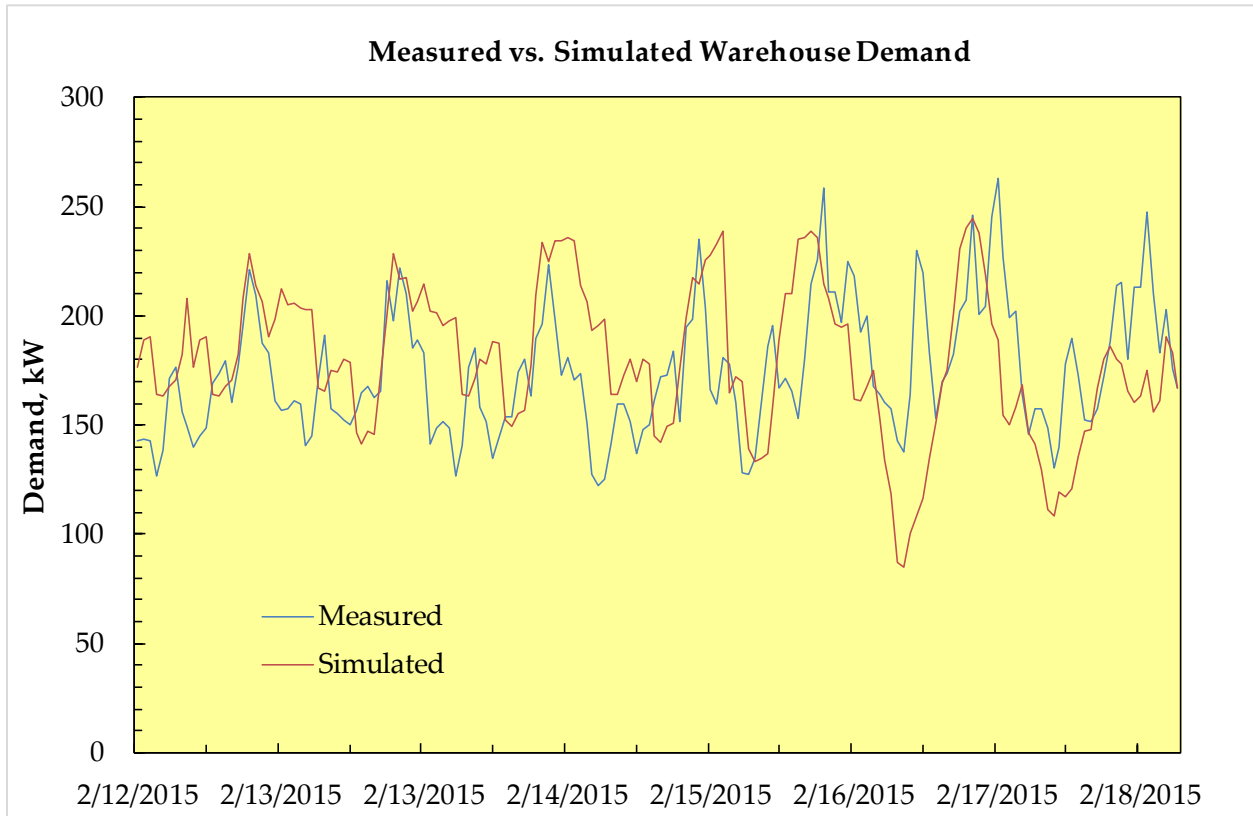
Table 12 presents the acceptable tolerances for monthly and hourly data calibration according to ASHRAE Guideline 14. Our initial models were validated against the measured data to achieve the acceptable monthly tolerances based on the required MBE and CV(RSME).

Table 12: Acceptable calibration tolerances

Calibration Type	Index	Acceptable Value
Monthly	$\text{MBE}_{\text{month}}$	±5%
	$\text{CV}(\text{RMSE}_{\text{month}})$	15%
Hourly	MBE_{hour}	±10%
	$\text{CV}(\text{RMSE}_{\text{hour}})$	30%

Figure 9 shows the measured refrigerated system demand power plotted against the simulated data for every hour during a week in February 2015. NMBE and CV(RMSE) for this comparison are 4.7% and 18.8%, respectively, indicating that the model's predictions of refrigeration system demand show an acceptable agreement with the measured data. Hourly comparison between measured and simulated demand are affected by many uncertainties and external factors such as food transportation in and out of the warehouse.

Figure 9: Comparison of Refrigerated System Demand between Measured and Simulated in a Week of 2015



5.3 Estimation of DR Potential

In this study, ten wireless temperature probes were deployed to measure the air temperature within one zone of the facility. Wireless connection to one of the sensors was lost after the start of the data collection; therefore, nine of ten sensor's temperature data were collected to get the average temperature of the space. Figure 10 shows the measured average temperature of the warehouse for one week in March. On March 16th, 2015 a test DR event was performed at the facility. The results of this test event were used for evaluating the simulation of dynamic response of system and space temperature in DRQAT-RW. Pre-cooling as a standard operating procedure was performed prior to the test event and the measured temperature during the event is shown in Figure 11 and Figure 12.

Figure 13 presents the refrigeration system's compressor load on baseline and DR days. The baseline load was calculated as the average demand of the previous four days from 3/12 to 3/15. The estimated load shed during the DR event hours was about 105kW. The average compressor load on 3/17 and 3/18 was 165kW during the DR event hours, which was much higher than that of the previous baseline days. Therefore, this fluctuation of the compressor load leads to the uncertainty of the load shed estimation on the DR test day.

Figure 10: Measured Average Temperature within a Space of Warehouse (One week in March, 2015)

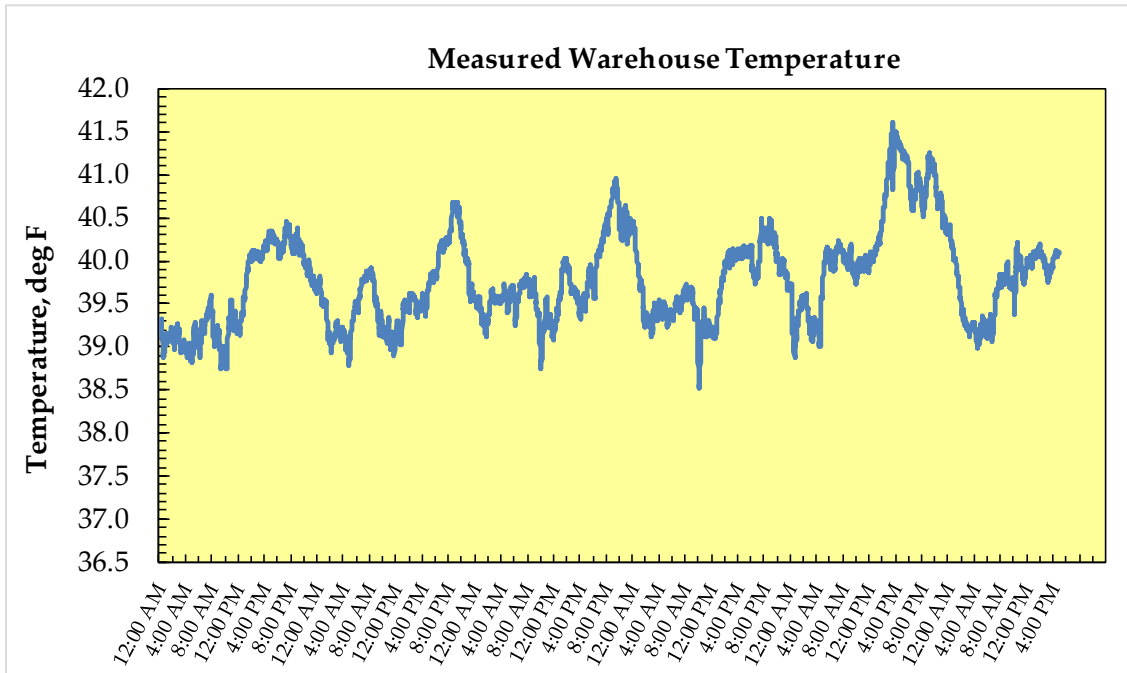


Figure 11 Temperature measurement from all 9 probes installed at the warehouse in various spatial locations.

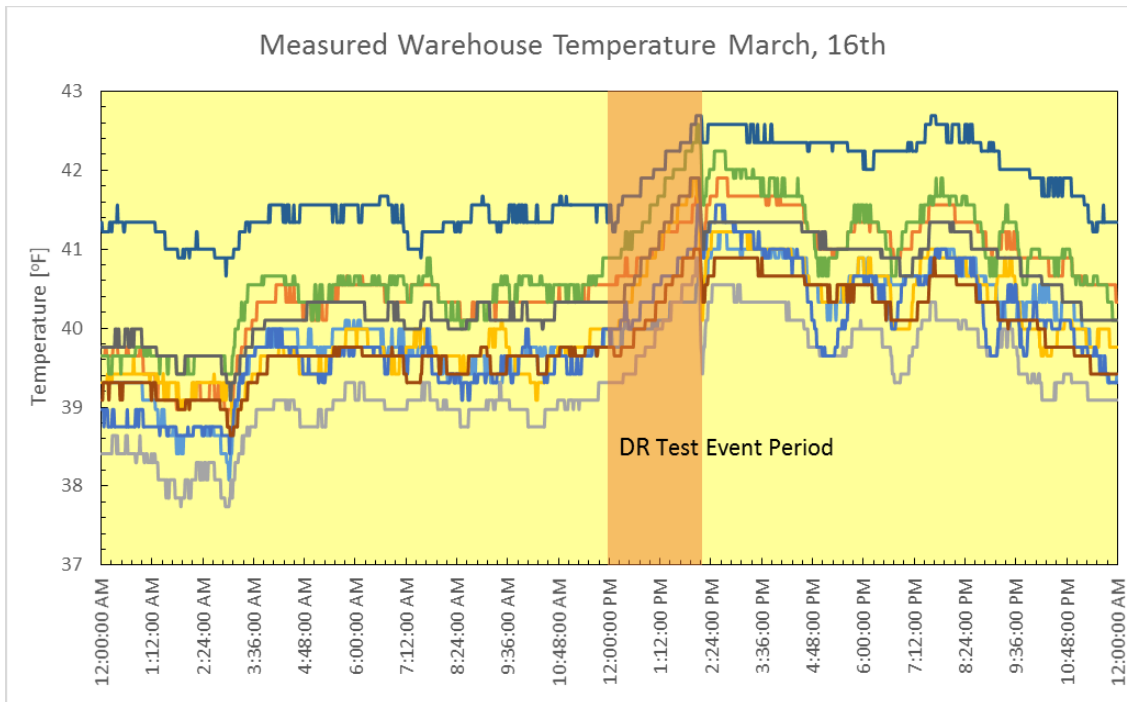


Figure 12: March 16th DR test at the warehouse average space temperature. Precooling was done starting at 3am, 9 hours prior to the event.

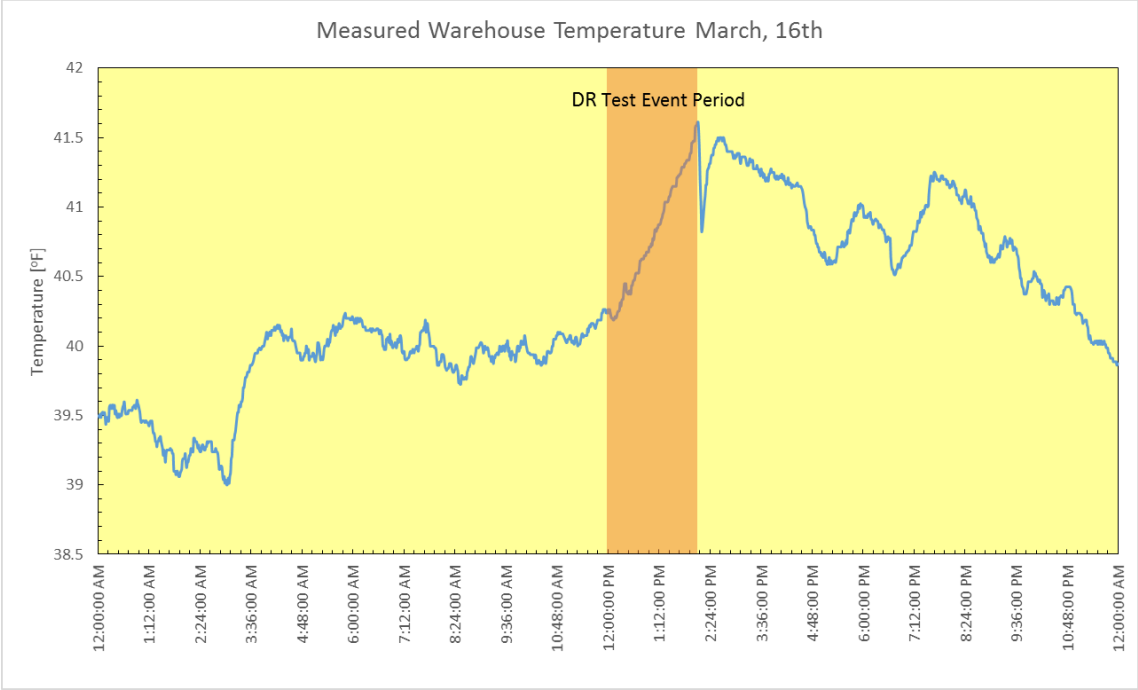
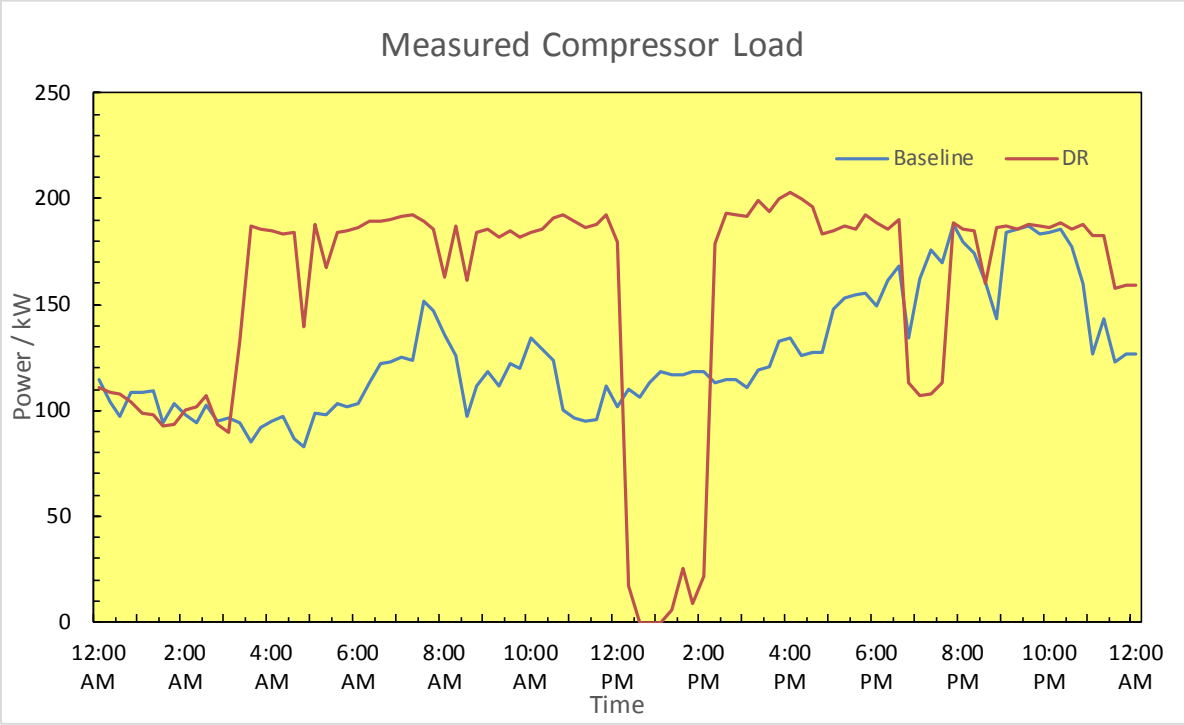


Figure 13: March 16th DR test at the warehouse (Compressor Load). Precooling was done starting at 3am, 9 hours prior to the event.



Next, DRQAT-RW was used to simulate the DR event at the same facility and the result is shown in Figure 14. The simulation does not show any fluctuation in the space temperature when the system is running normal operations. Without model calibration and exact refrigeration unit capacity input, baseline temperature will not be an accurate representation of the actual space temperature. However, the response to the DR test in the simulation will be accurate even without model calibration. In order to simulate the dynamic response of the model, the DR control strategy was performed in the DRQAT-RW's, event simulation. As shown in Figure 13, it can be seen that the refrigerated space temperature rise by 1.5°F during the DR test, which is in close agreement to the actual measured temperature rise during the DR test. Figure 14 shows the simulated refrigeration system demand of the baseline and the DR scenario. It can be clearly seen that the compressor load was reduced to zero when switching off the compressor during the DR event hours.

Figure 14: Simulated Refrigerated Zone Temperature on a DR Test Day

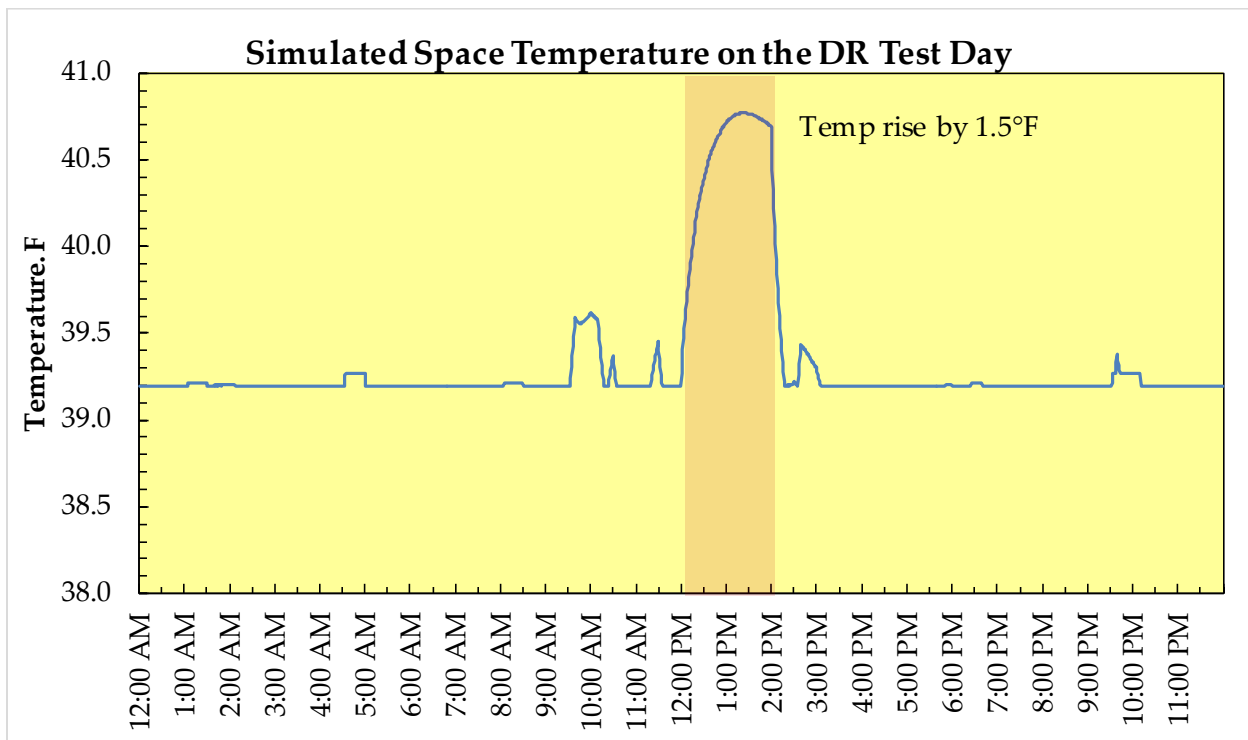
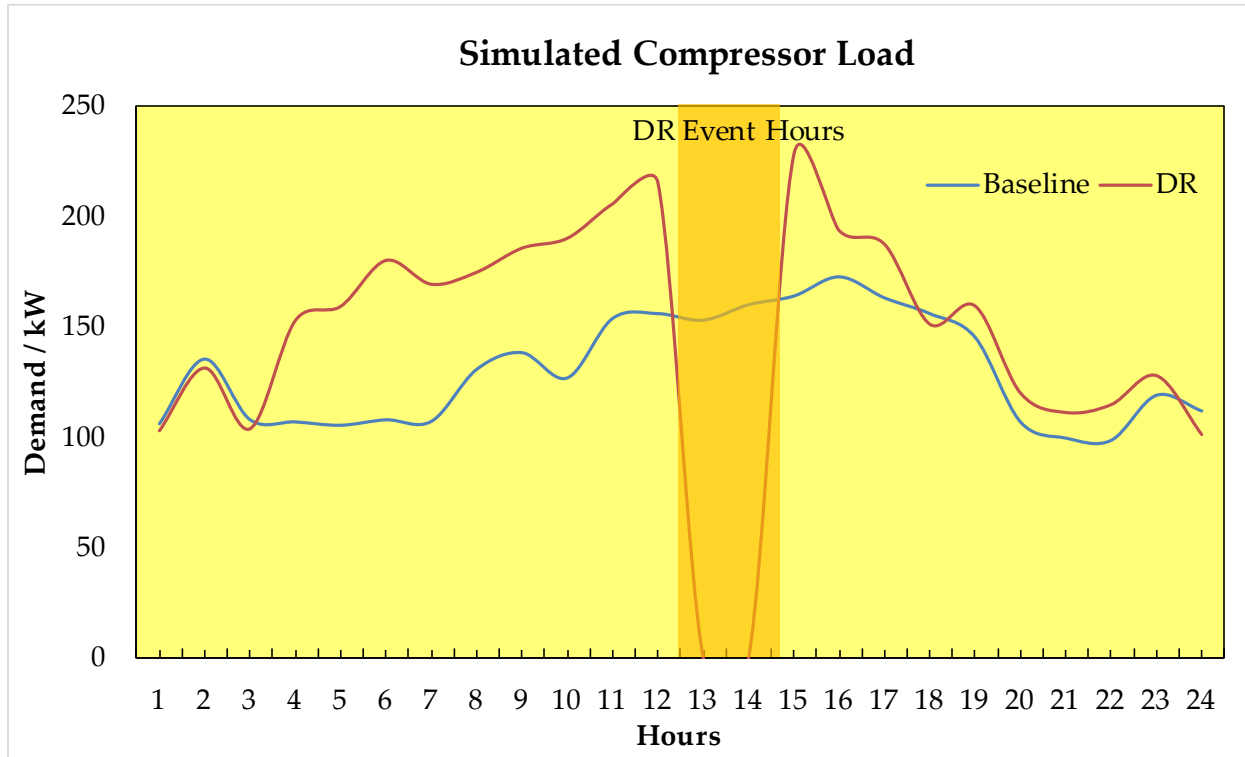


Figure 155: Comparison of Simulated System Demand between Baseline and DR



The estimated demand reduction during the two hour DR event is 157 kW, which is very close to the measured load shed based on the baseline days of 3/17 and 3/18. As presented in Table 12, precooling and DR test event compressor load of all baseline days were 123kW and 132kW in average, respectively. The simulated load shed from compressor load is 20% higher than the load measured on the DR test day, which is still within the acceptable model tolerances.

Table 133: Measured and Simulated Baseline & DR Days' Demand during Precooling and DR Event Hours

Baseline Days	Demand during Precooling Hours (kW)	Demand during DR Event Hours (kW)
3/12/2015	103	100
3/13/2015	106	109
3/14/2015	114	127
3/15/2015	118	123
3/17/2015	144	151
3/18/2015	154	179
Average	123	132
Baseline Day (Simulated)	126	157
DR Test Day (Measured)	182	10
DR Test Day (Simulated)	181	0

CHAPTER 6:

Conclusion and Future Work

Previous work identified refrigerated warehouses to be a good candidate for DR. The thermal mass available at refrigerated warehouses allows the refrigeration system to be turned off during peak hours, resulting in significant demand reduction at refrigerated warehouses. Understanding the temperature rise and the impact of that temperature rise on the stored product is crucial in facility's decision for taking part in DR. DRQAT-RW provides a decision making tool for facilities contemplating DR participation.

6.1 Conclusions

The tool development of DRQAT-RW bridges the gaps in current modeling capabilities of refrigeration system performance. DRQAT-RW empowers warehouse owners and operators to simulate space temperature for their warehouse space during DR events. In addition it provides information on the deterioration rate of stored product in response to the temperature rise during the DR event. DRQAT-RW is a “wrapper” for the backend EnergyPlus simulation engine. Modeling capabilities of EnergyPlus include less than an hour time steps, modular refrigeration system, heat balance-based zone simulation, and treating the stored product as thermal mass in the zone.

Based on the previous experience about EE and DR in refrigerated warehouses, a set of EE and DR measures and relevant model parameters are summarized as references of the tool development. The interface of DRQAT-RW allows simulation users to perform the analysis of various EE and DR measures in refrigerated warehouses in a fast manner. In addition, a food storage model has been successfully implemented in DRQAT-RW, which will enable users to assess the impacts of DR measures on zone temperature changes and associated deterioration rates of stored food. Deterioration rate is greatly influenced by temperature and is generally reduced as temperature is lowered, which is used in the DRQAT-RW model for evaluating the impact of temperature changes on the food quality.

In this study, an innovative modeling of the stored products in refrigerated warehouses was developed using the EMS feature within EnergyPlus. By overwriting the thermal properties and amount of the internal mass dynamically, EMS model is used to simulate the food transportation in each zone of the refrigerated warehouse. A few cases are modeled and simulated in EnergyPlus to investigate the effects of stored goods addition/removal on the zonal cooling load. Significant differences of cooling load rate between each test case were observed in the study, which indicated the importance of the modeling of stored products transportation in refrigerated warehouses.

Last, the model of DRQAT-RW was tested and validated at an actual cooler facility in southern California. An analysis on the measured and simulated space temperature resulted in acceptable tolerance values suggesting that even without model calibration DRQAT-RW's simulation engine is capable of predicting accurate space temperature. In addition the model

accurately predicted 1.5°F temperature increase due to a DR event at the test facility. The predicted temperature rise precisely represents the facility's behavior during an actual event during which 9 probes collected real-time space temperature. The estimated demand reduction during the two hour DR event is 157 kW, which is very close to the measured load shed based on the baseline days of 3/17/2015 and 3/18/2015. It was found that the compressor load had large fluctuations before and after the DR test day. Using the average demand of all baseline days, the simulated load shed from compressor load is 20% higher than that measured on the DR test day, which is still within the acceptable model tolerances.

6.2 Future Work

The primary outcome of this project was the development of a software tool, DRQAT-RW, which is a relatively simple “wrapper” around a very complex simulation engine, EnergyPlus, for simulating various EE and DR measures in refrigerated warehouses. Hence, there are a few feature enhancements that need to be added to the next version. Those features can be summarized as:

- Automated optimization of EE and DR strategies to produce the greatest demand and cost reductions while maintaining the food quality.
- Make weather data customization more user friendly and enable real weather data for simulation in DR season.
- Develop the procedure of model auto-calibration to improve the model prediction value.

Larger scale deployment and testing of this tool is an important future work. This will allow us to further validate the functionality of the tool and make improvements based on user feedback. LBNL will work with industry partners such as VaCom Technologies, Energy Solutions, and Investor Owned Utilities to promote the use of DRQAT-RW.

GLOSSARY

Term	Definition
ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
AU	Air handler Unit
CVRMSE	Cumulative Variation of Root Mean Squared Error
DOE	Department of Energy
DR	DR
DRQAT	DR Quick Assessment Tool
DX	Direct Expansion
EE	EE
EMS	Energy Management System
HID	High Intensity Discharge
HMI	Human Machine Interface
HP	Horsepower
HVAC	Heating, Ventilation and Air-Conditioning
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
M	Measured
MBE	Mean Bias Error
N	Number of Months
PLC	Programmable Logic Controller
RAD	Rapid Application Development
RW	Refrigerated Warehouse
S	Simulated
SCT	Saturated Condensing Temperature
VFD	Variable Frequency Drive

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