Lessons Learned from 15 years of Refrigerated Facility Simulation

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Topics

- Simulation tool background
- California new construction incentive program
- Lessons learned
- Incremental analysis case study
- Simulation limitations and challenges
Simulation tool background

- 1993 – need for refrigeration simulation tool:
  - Supermarket emphasis (space/fixture interaction)
  - Address “component” based refrigeration systems
- Funding by CA utilities and others
- Completed in 1998 as DOE2.2R
- Key aspects for refrigeration analysis:
  - Mass flow based to allow component-level study
  - Built-in explicit control strategies
  - Detailed display case model
- Plus: building envelope, HVAC, lighting
Key attributes for supermarkets

- Balance between HVAC systems, fixtures, infiltration, ventilation air and controls
- Disaggregated display case loads:
  - Transmission from space
  - Air exchange with space (sensible and latent)
  - Fan, lights, heaters with schedules and controls
  - Defrost heat, recovery over time
- Detailed refrigeration system modeling
- Heat recovery from refrigeration
  - Controls for holdback valves, various strategies
Key attributes for warehouses

- **Mass-flow based system modeling:**
  - Two stage systems (and cascade HX)
  - Subcooling, desuperheating

- **Part-load controls and group staging controls**

- **Controls match common efficiency measures:**
  - Ambient reset, variable speed condenser control
  - Variable speed air unit controls
  - Floating suction controls

- **Infiltration and inter-zonal mass exchange:**
  - Density driven air exchange (ASHRAE formulas)
  - Wind driven air entry
California new construction program

- **Savings By Design:**
  - Statewide incentive program for efficient new construction funded by public goods charge and administered by four major utilities
  - Separate program for supermarkets and refrigerated warehouses, due to special analysis and base case for refrigeration systems
  - Savings and incentive based on improvement over Title 24 (lighting and HVAC) and standard practice for refrigeration systems
  - Emphasis on design assistance to support owner investment decisions
  - Very limited recommendations on system sizing
New construction project delivery

- **2001-2008 refrigeration projects:**
  - Yearly energy savings: 230 million kWh
  - Peak demand reduction: 34,000 kW
  - Approx. annual savings: $28 million

- **320 retail food stores**
- **150 refrigerated warehouses & food plants**
- **Mandatory whole-facility simulation for all refrigeration projects**
- **Savings vs. Title 24 or defined standard practice**
- **Plus analysis of many existing facilities for retrofit**
Example projects

- Large new refrigerated warehouse projects:
  - Grocery distribution complex, 2 million SF
  - Ice cream manufacturing and distribution facility
- Diverse process plants:
  - Dairies, wineries
  - Packaged salads
  - High tech mushroom production facility
  - Seasonal fruit and produce pre-cooling & storage
- Retail food chain new prototype development
- Nationwide retail study (skylights, reclaim)
- Regional best practices & economics analysis
Refrigeration base case definitions

- Lack of code required a “standard practice” basis
- Base case definitions were developed for:
  - Warehouse insulation
  - Condenser size (approach)
  - Specific efficiency method and standards for condenser power (condenser fan/pump Btuh/Watt)
  - Minimum condensing temperature setpoint
- Considerable flexibility in compressor & system type, with efficiency vs. associated base case
- Use *either* air-cooled or evap-cooled as base case against which efficient options are evaluated
Typical supermarket measures

- **Lighting**
  - Lighting power density, skylights, controls

- **Refrigeration**
  - Condenser sizing, specific efficiency (low fan power)
  - Floating head pressure with variable speed drives, variable setpoint control
  - Mechanical subcooling
  - Floating suction pressure
  - Efficient evaporator coil motors

- **HVAC**
  - High EER package units
  - Variable speed drives for air handler motors
  - Heat recovery from refrigeration

- **Display fixtures**
  - Efficient case fan motors
  - Efficient lighting (LED lights)
  - Lighting control
  - Anti-sweat heater control
Industrial refrigeration measures

- **Increased insulation, cool roof, high speed doors**
- **Refrigeration systems:**
  - Condensers, increased size and reduced fan power
  - Floating head with variable speed & setpoint
  - Variable speed control of air unit fan motors
  - Variable speed compressor control
  - Other system automation
- **Other specialized measures:**
  - Close approach HX (e.g. pasteurization regen)
  - Cool-recovery process water heat exchangers
  - Refrigeration heat recovery
Evolving base case standards

- As technology evolved and adoption increased, base case assumptions changed.
- **Supermarkets changes (03 to 09):**
  - Standard anti-sweat heater control
  - Standard EC motors in cases
  - Standard PSC then EC motors in walk-ins
  - Reduced minimum head pressure setpoint
  - Lower light level, mandatory skylights
- **Refrigerated warehouses changes (09):**
  - Condenser variable speed/floating head pressure
  - Air unit variable speed
  - Compressor variable speed (certain conditions)
Lessons learned

- Timing drives analysis focus
- A lot of discussion about “loads”
- Results from simulation work opens useful discussion concerning:
  - Design vs. actual loads
  - Facility design basis
  - Component performance
  - Cost effectiveness
  - How systems really operate
  - Control strategies & capabilities
  - Equipment sizing
  - Vendor interactions
- Simulation results drive interest in field studies
- Decision making process (i.e. *business decisions are financial decisions*)
Timing impacts study focus

- **Early involvement:**
  - Fundamental concepts
  - Help define loads and expectations
  - Building shape and orientation (e.g. high rise)
  - Refrigerant choices and system types

- **Late involvement:**
  - Bolt-on improvements
  - Control strategies and setpoints

- **Chains with specification process:**
  - Continuous improvement – studies apply to future
  - Ongoing review of current design choices
Lessons – Warehouses loads

- **Consistent large gap between system design capacity and peak simulation loads:**
  - Some obvious (40% floor load in large cooler)
  - Common rule-of-thumb and “last job” sizing
  - Simulation only as good as inputs
    - Some elements are guesstimates for design *and* simulation
  - Equipment catalog vs. “real world” variance
  - Need capacity for expansion, outages, aging

- **Loads difference resulted in study efforts:**
  - Field measurements and studies
  - Installation of real-time performance monitoring
Lessons – Equipment performance

• **Air units often don’t perform as expected:**
  - New air units not reducing TD at lower loads
  - Old air units running 50-100% higher than design TD at design loads

• **Condensers often don’t perform as expected:**
  - Higher TD at part load/off-design than calculated on large evaporative condensers
  - Supermarket condensers frequently impacted by piping practice (excessive backflooding and cycling effects), may operate at double expected TD

• **Small system details can have very big impact**
  (e.g. suction regulators and big capacity steps)
Produce facility example

- Simulation studies for produce facilities showed fan power and associated cooling as an unexpectedly large fraction of energy use.
- Field study undertaken at four locations to measure cooling load and fan power vs. total refrigeration power:
  - All locations pre-cool and store similar fruit.
  - All have seasonal operations.
  - Similarly designed ammonia refrigeration systems.
  - Four month study – July through October.
Produce facility example

- Comparison of seasonal fan power, including fan heat load on compressors for four locations through cooling season

<table>
<thead>
<tr>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td>Compressor HP</td>
<td>825</td>
<td>675</td>
<td>1,035</td>
<td>510</td>
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<tr>
<td>Capacity, Tons</td>
<td>900</td>
<td>713</td>
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<td>414</td>
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<td>Peak Load, Tons</td>
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<tr>
<td>Total fan kWh</td>
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<td>150,700</td>
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<td>177,200</td>
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<tr>
<td>Fans % of cooling load</td>
<td>22.0%</td>
<td>16.6%</td>
<td>29.9%</td>
<td>17.6%</td>
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<tr>
<td>Fans % of total kWh (1)</td>
<td>46.6%</td>
<td>35.7%</td>
<td>52.8%</td>
<td>41.9%</td>
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</table>

(1) Including kWh for cooling load on compressors

- Study preceded the wide adoption of variable speed fan controls in produce cooling facilities
Lessons – Supermarkets

• **HVAC system operation:**
  • Cooling hours are very low peak load annual frequently less than half or third of installed tonnage
    • Subsequently verified with history collection
  • Heat reclaim evaluated extensively, typically small electricity impact for large gas savings

• **HVAC interaction with refrigeration:**
  • Difficult to achieve refrigeration savings with lower humidity via HVAC system (reheat is not free)

• **Increased insulation seldom pays (in CA anyway):**
  • Supermarket is heating majority of the year
  • Use less insulation and invest capital elsewhere …
Lessons – Supermarkets

• **Findings contrary to expectations:**
  • No savings from floating head pressure on systems with low efficiency condensers and fan cycling in moderate CA climates
  • Low fan power condensers have poor economics compared with average power condensers plus variable speed and variable setpoint control
  • No savings on condensers larger than 10/15 F TD

• **Air-cooled condenser motor efficiency:**
  • Direct drive condenser motor input power typically is not published and is often not related to referenced horsepower
Lessons – Field verifications

- Utility program field verifications provided observations to compare with analysis results:
  - Skylight savings often far less than theoretical savings due to control variations
  - Control operation often very different than simulation – fast response from feedback control even though load changes slowly
  - Sensor error can have large impact on efficiency; easy for humidity sensor drift to cause simultaneous heating and cooling with no dehumidification
Financial presentation

- **Simulation inherently resolves system interactions, allowing marginal analysis**
- **Most savings are not additive:**
  - $15\% + 15\% + 15\% + 15\% = 60\%$ savings (??)
  - $0.85 \times 0.85 \times 0.85 \times 0.85 = 0.52 = 48\%$ (at best)
- **Two methods for presenting economics:**
  - Combinations of measures
  - Incremental comparison
- **Incremental savings – what to start with?**
  - Simplest technology?
  - Fastest payback?
Examples of Combinations of Measures:

- Combination 1: Measures A, B, C and D
- Combination 2: Measures A, B and D

This presents to choices, typically better when measures must be designed as one combination or another.

Example of Incremental Comparison:

- Measure A
- Measure A and B
- Incremental Savings of B – A
- Measure A, B and C
- Incremental Savings of C – (A and B)
Incremental savings: FHP case study

- Cold storage warehouse in Stockton, CA
- Evaporative condenser (average efficiency)
- Hourly simulation analysis
- Base case = fixed setpoint at 85 F SCT
- Analysis options
  - Float SCT using fixed setpoint
  - Add variable setpoint
  - Add variable speed with fixed setpoint
  - Add variable speed with variable setpoint

- Results show importance of control strategy
Variable setpoint floating head

![Graph showing ambient temperature and condensing temperature setpoint](image-url)
Fixed setpoint

<table>
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<tr>
<th></th>
<th>Annual Energy, mWh</th>
<th>Control Options</th>
<th>FHP</th>
<th>FSP</th>
<th>VSP</th>
<th>VFD</th>
<th>Savings</th>
<th>Payback</th>
<th>NPV</th>
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Variable setpoint

Annual Energy, mWh

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Control Options

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<th>FHP</th>
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### Fixed setpoint and variable speed

#### Annual Energy, mWh

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Variable setpoint and variable speed

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<th>FSP</th>
<th>VSP</th>
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Simulation limitations & challenges

- **Inherent difference in simulation and real control:**
  - Simulation assumes “perfect” control operation that matches load requirements
  - Standard feedback controls react quickly even though underlying loads may change very slowly

- **Adjust simulation parameters for realistic results:**
  - Program speed overrides to address realistic temperature/speed control response, particularly related to “third-power” fan savings
  - Choose settings to address impact of transients, compressor cycling between stages, control valve effects
Simulation limitations & challenges

- **Evaporative condenser ratings:**
  - Published capacity factor tables lack “average” conditions, simulation extrapolates

- **Air-cooled condenser ratings:**
  - Tables assume perfect Q=UATD at any TD and EAT. Questionable for simulation (and design)

- **Semi-hermetic compressor RGT rating:**
  - Return gas temperature based on 65 F, fully productive refrigeration
  - Correction factors are not published (electronic ratings allow other RGTs using simple density adjustment)
Future improvements

- **Program features:**
  - Secondary cooling loops and heat exchangers
  - Refrigeration/HVAC water loop integration
  - Improved air unit model

- **Equipment information:**
  - Accurate motor watts for condensers and air units
  - Improved part-load/off-design performance data for air- and evap-cooled condensers
  - Adoption of rating standards and certification of equipment performance for refrigeration equipment
  - Refrigeration simulation inherently at component level, so need component performance data
Improvements needed – equip info

Example – evap condenser heat rejection factors

Lowest condensing temperature on chart is 85 F vs. typical operation at 70 F SCT or lower

Adequate for peak design, but without extended ratings, energy analysis requires guesswork
Improvements needed – equip info

Example: commercial refrigeration compressors

<table>
<thead>
<tr>
<th>RATING CONDITIONS</th>
<th>LOW TEMPERATURE</th>
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<tbody>
<tr>
<td>65°F Return Gas</td>
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<tr>
<td>9°F Subcooling</td>
<td></td>
</tr>
<tr>
<td>95°F Ambient Air Over</td>
<td></td>
</tr>
<tr>
<td>60 Hz Operation</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Condensing Temperature °F (Sat Dew Pt Pressure, psig)</th>
<th>Evaporating Temperature °F (Sat Dev)</th>
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</thead>
<tbody>
<tr>
<td>130</td>
<td>-30 (3.5)</td>
</tr>
<tr>
<td>(354)</td>
<td>-40 (4.5)</td>
</tr>
<tr>
<td>C</td>
<td>26300</td>
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<td></td>
<td>35800</td>
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<td>%</td>
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</table>

HFCs Require Use of Polyoil Ester Lubricant Approved on Form 93-11

- Rated capacity at 130°F and -30°F including all superheat = 45.6 Btuh/Lb refrigerating effect (404A)
- At same mass flow, refrigerating effect with 10°F superheat is 28.8 Btuh/Lb, 37% less
- Mass flow would be higher with RGT lower than 65°F, but relevant data to allow analysis is not published

Published Rating Conditions at 65°F RGT. Rated capacity includes all superheat from -30°F to 60°F.
Conclusions

- Simulation is useful at early stages, but also effective to fine-tune control strategies and set performance expectations.
- Essential to include experience and judgment in analysis assumptions, but also have to “follow” simulation results that may be counter-intuitive.
- Essential to review intermediate results, system and hourly reports for sanity and consistency.
- Moving perspective from peak design loads to hourly energy analysis is a challenge.
- For many owners, accurate economics has become more important than incentives.
Questions?