Experiences with Modeling Supermarket Energy Use and Performance

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Introduction and Background

Supermarkets are unique class of commercial buildings that integrate heating, cooling, and ventilation (HVAC) systems as well as refrigeration systems into a single facility. Traditional building simulation tools do not include the detailed models necessary to properly consider the performance of and interactions between all of these systems. While mainstream building simulation tools generally can model building and HVAC performance, the provisions to consider refrigeration system performance are often weak or non existent. Similarly, software tools that are able to model refrigeration system performance typically do not have the ability to predict building heating and cooling loads and HVAC system performance. Clearly, integrated software tools are necessary to properly simulate the supermarket as a system so that the tradeoffs between these competing subsystems can be understood. Only an integrated analysis will allow the supermarket system be “optimized” to provide the lowest energy use and environmental impact with the lowest capital expenditure. To address this unmet need, EPRI has developed the Supermarket Simulation Tool (SST).

SST has been developed based on the practical experiences of EPRI over the last 15 years. EPRI has monitored the detailed performance of several supermarkets various locations throughout the USA. This field experience has demonstrated the importance of treating the supermarket as an integrated system. To address the unique challenges of a supermarket, EPRI has worked to develop new technologies such as the dual path HVAC system. This technology efficiently provides dehumidification so that lower humidity levels can be maintained to reduce refrigeration system energy use. Using this more efficient dehumidification system typically minimizes total annual energy costs.

Experiences from field tests have also shown that recovering waste heat from the refrigeration system condensers is a key element of efficient supermarket operation. The year around cooling effect provided to the space by the display cases means that space heating loads are more important in this application than in other commercial buildings. Therefore, capturing waste heat to offset these loads can provide substantial energy savings. Similarly, new refrigeration systems that reduce refrigerant charge but impede the ability to do heat recovery must be carefully considered if the expected environmental benefits are to be realized.

SST has been developed to help the supermarket industry address these types of issues. The tool is intended give industry professionals the ability to evaluate and understand the complex interactions in these energy intensive buildings.

Technical Features of SST

SST is an hourly building simulation program that also includes a detailed model of a supermarket refrigeration system. Like other building simulation programs, SST uses hourly weather data to predict building loads and HVAC energy use. It can consider facilities with multiple zones and HVAC systems. Any number of the refrigeration systems can also be modeled with the refrigeration or cooling effect able to be assigned to one or more zones.

Detailed display case and "walk-in cooler" (or cold room) models consider the impact of indoor humidity levels on the refrigeration loads, defrost requirements, and anti-condensate heater operation. Similarly, the cooling and dehumidification provided to the space by the display cases are factored into the zone heat and moisture balance calculations. SST also includes robust models of the HVAC equipment and controls commonly used supermarkets so that the tradeoffs of various equipment configurations and dehumidification set points can be considered.

SST also properly considers the use waste heat from the refrigeration system for space heating. This allows the impact of lowering the minimum refrigeration condensing pressure (i..e., floating the head pressure) to be traded off against the ability to reclaim condenser heat for space heating at given condensing temperature.

The integration of the refrigeration and HVAC equipment on a common water loop can also be simulated by SST. The integrated water loop approach has the advantage of greatly reducing the refrigerant charge compared to traditional air-cooled systems. Combining water-to-air heat pumps on a water loop with water-cooled refrigeration equipment allows for a centralized cooling tower for heat rejection during the summer. It also provides the means to efficiently recover heat from the refrigeration system for space heating using heat pumps.

SST User Interface

SST is an easy-to-use Windows application that allows a novice user to quickly construct a model of the supermarket. The interface includes several features to that allow the user to quickly assemble the components necessary to define the refrigeration, HVAC, and building envelope systems. Figure 1 shows the refrigeration rack editor where the various components on each refrigeration rack can be added, modified, or removed. Similar editors exist for HVAC and the building envelope sections of the program. Components on a system are represented as "icons" and can be defined or modified by clicking on the item. The performance of each component is typically modeled using algorithms that are consistent with the manufacturer's available data (for instance coefficients compiled according to ARI Standard 540-91 for compressors). The use of manufacturer-generated performance data allows the user to quickly assemble the information necessary to simulate a supermarket.

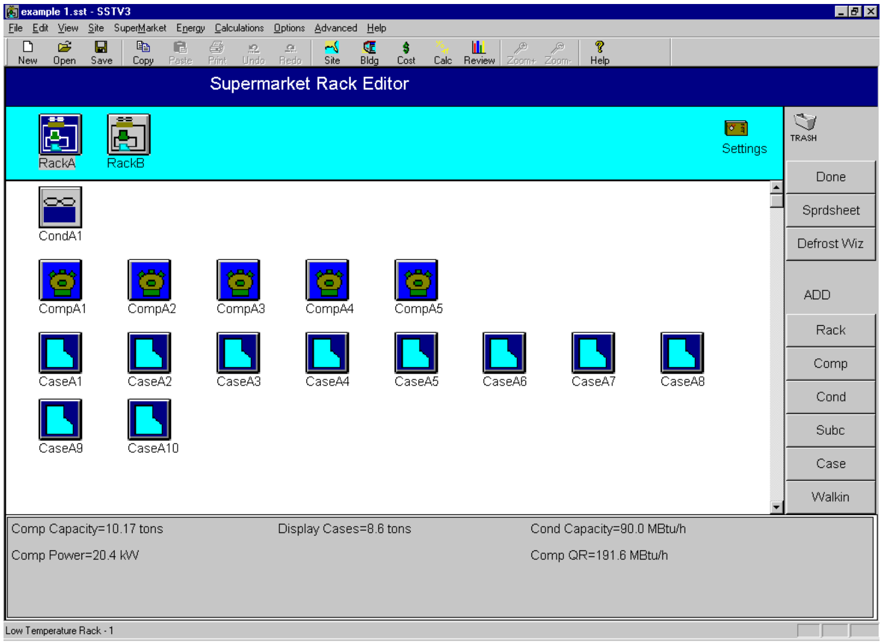

Figure 1. Rack Editor Screen in SST

This approach has facilitated the generation of data for a large library of components for compressors, display cases and other major components, easing the data entry burden on the user. Figure 2 shows how the data for a specific compressor are loaded into SST. Performance data on more than 1,600 compressor models from two manufacturers are available in the current libraries. A similar number of components for display cases will also soon be available as well.

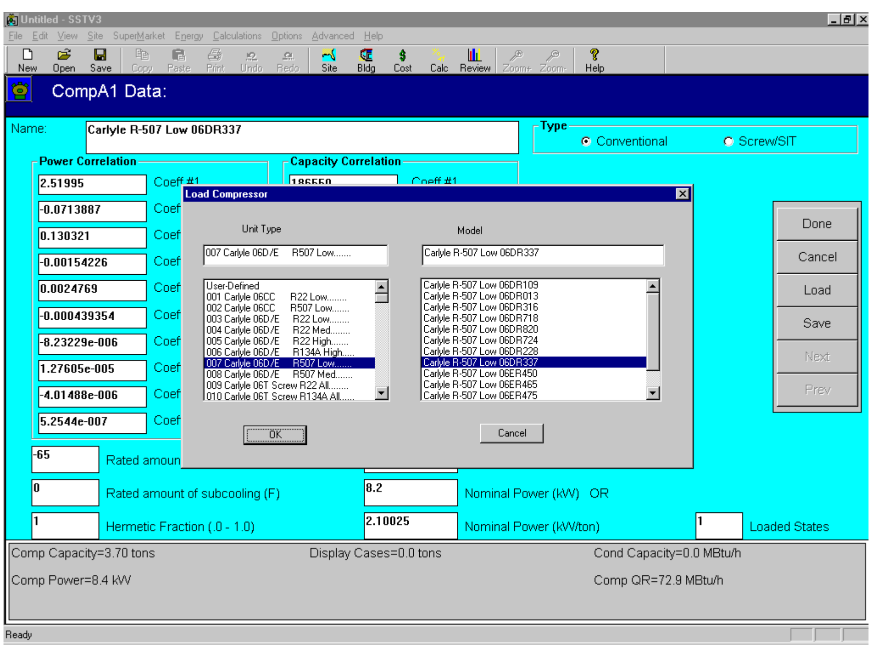

Figure 2. Loading a Compressor from the Pre-Defined Library

A similar editor is available to define and configure the HVAC system in each zone. Figure 3 shows the layout for a single path system with a single cooling coil (air-cooled DX unit), supply fan, and heating coil. The system also includes under case return ducts: so a portion of the sensible and latent cooling credits from the display cases are added to the return air stream. The specific performance, or properties, of each component is entered or viewed by clicking on that item.

Figure 4 shows the building envelope editor, where the description of the building envelope (or fabric) is described along with the schedule and magnitude of the internal loads.

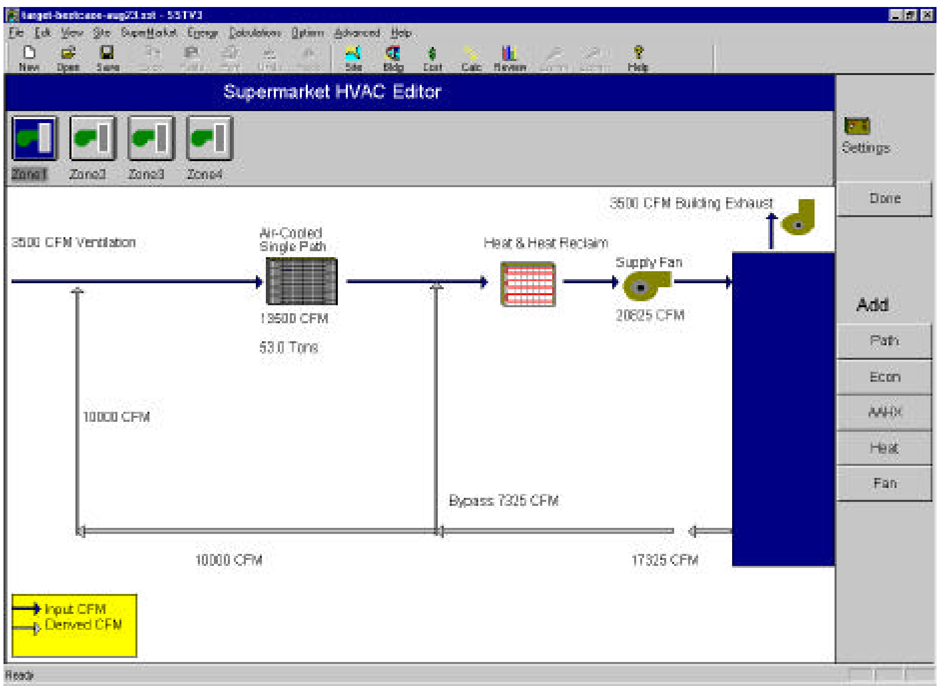

Figure 3. HVAC System Editor with a Single Path System in Zone 1

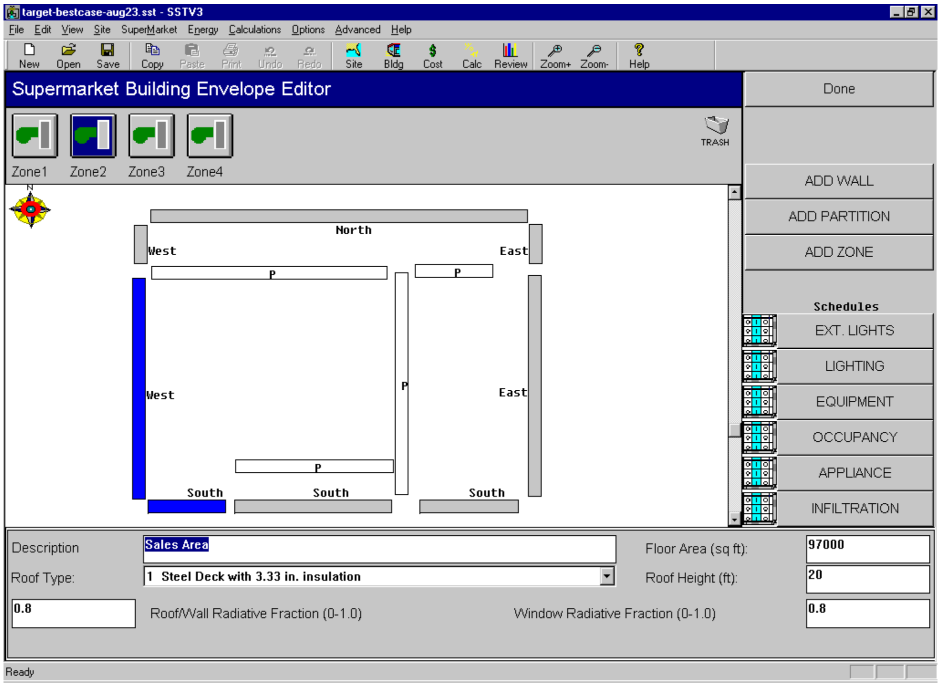

Figure 4. Building Envelope Editor with Zone 2 Highlighted

Case Study Example

SST has been used to evaluate various energy saving opportunities in a number of actual supermarkets. The case study described below is an evaluation of a large retail Super Center with grocery and discount department store merchandise combined in a single facility. The building has a total floor area of 16,200 m^2.

Baseline Model Development and Validation

The first step of the process was to develop a baseline model of the facility. The construction drawings, refrigeration equipment schedules, and HVAC equipment specifications were used as the basis to develop the model of the store. Key set points and other control parameter were also determined by collecting data from the building's digital control system and through discussions with the building operators.

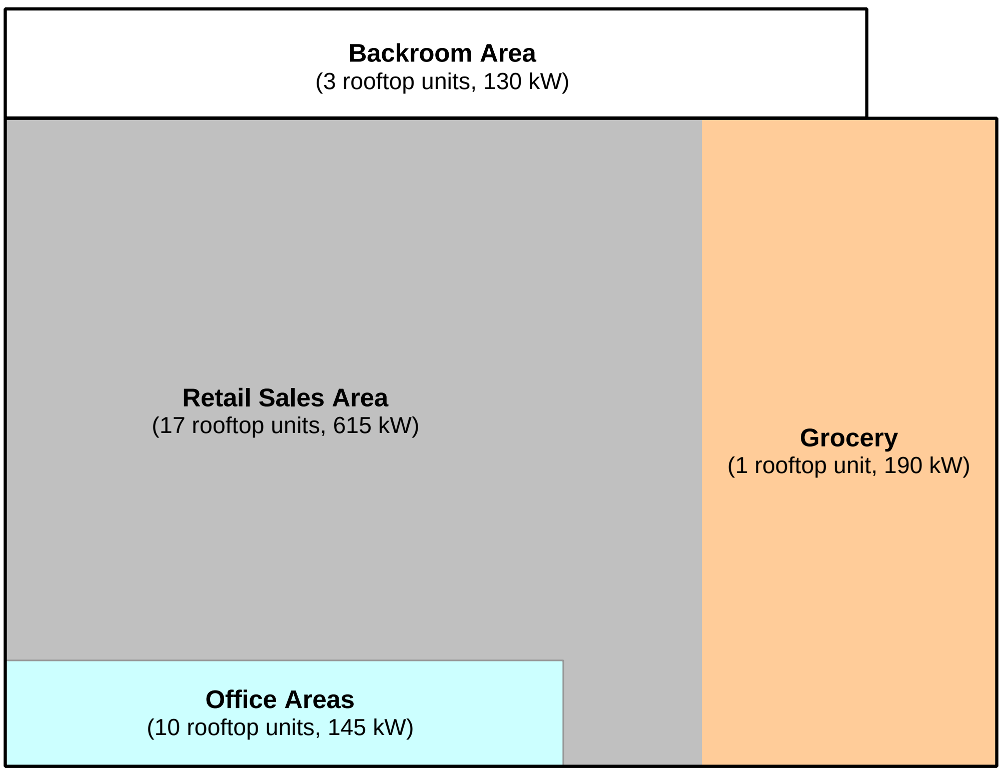

Figure 5. Layout of Retail Facility

As with any building simulation effort, several assumptions were made to simply the model and focus on the elements of interest. Some of the key assumptions are listed below:

- The large open sales floor was divided into two sections: a grocery area and a retail sales area (see Figure 5). The grocery area included a single custom HVAC unit designed for traditional grocery store applications. The multiple rooftop mounted air conditioner units on the other side of the store were lumped into a single cooling "unit" that served the large retail sales zone. The cooling effect provided by the display cases was assigned to the grocery area zone. Heat and mass transfer between these zones was simulated with a highly conductive "porous" partition with its UA value converted to an appropriate air flow rate – this approach simulated the close coupling of two "zones" occupying the same large space.

- The separately-conditioned office space scattered throughout the facility was combined into a single zone with its own internal loads, operating schedules, and lumped HVAC system.

- The backroom areas were combined into a single zone with its own heating and cooling set points. The refrigeration effect from many of the walk-in coolers or cold rooms in the store were assigned to this zone.

These approximations allowed the important aspects of facility performance to be captured without the burden of unneeded detail. Care was taken make the floor area, exposed wall area, equipment capacity, supply air volume, ventilation rates and other key parameters in all four zones summed to the actual values for the facility. Table 1 summarizes the building envelope information used in the model and Table 2 lists the HVAC details.

Table 1. Summary of Building Envelope and Internal Loads

Zone	**Floor Area (m^2)**	**Wall Area (m^2)**	**Window Area (m^2)**	**Peak Lighting (W/m^2)**	**Peak Equipment (W/m^2)**	**Peak Occupancy (-)**
Grocery Area	3,437	715	37	17.2	14.0	185
Retail Sales Area	9,012	687	19	16.1	5.4	485
Office Areas	1,905	353	19	19.4	16.1	62
Backroom Areas	1,858	1,059	19	15.1	16.1	60
Total Store	16,212	2,815	93	18.3	7.5	792

Note: Wall and roof materials were taken from drawings. Internal loads in each zone were assigned separate hourly/weekly schedules based on observed facility operating patterns and control settings.

Table 2. Summary of HVAC System Configuration

	Installed Cooling Capacity (kW)	**Supply Flow Rate (l/s)**	**Ventilation Flow Rate (l/s)**	**Norm. Supply Flow Rate ($l/s\text{-}m^2$)**	**Norm. Vent. Flow Rate ($l/s\text{-}m^2$)**	**Vent. per Occupant (l/s)**
Grocery Area	186	9,828	1,652	2.86	0.48	8.9
Retail Sales Area	615	32,423	4,819	3.60	0.53	7.6
Office Areas	141	7,079	1,321	3.72	0.69	21.3
Backroom Areas	127	7,457	755	4.01	0.41	12.6
Total Store	1,069	56,787	8,547	3.50	0.53	9.3

Notes: Rated cooling efficiency at ARI Standard 360 conditions (but without the supply fan) is 2.9 W/W [10 Btu/Wh] for the grocery area unit and 3.8 W/W [13 Btu/Wh] for all other units.

The details for each component (display case, cold room, compressor, condenser, subcooler etc) on each refrigeration rack were also defined to buildup the refrigeration system. The available data provided by the refrigeration system manufacturer was used where provided and default or generic input parameters were used when manufacturer-specific information was unavailable.

Several very similar stores had been built and operating in various locations in the USA. Utility data from one of these locations were used to verify the model. Figure 6 compares the utility data from a store in Stone Mountain, Georgia to the daily results from SST using typical year weather data for Atlanta. The total facility energy use data are plotted versus ambient temperature. The utility data are based on the average daily energy use over each monthly billing period as well as the average ambient temperature data for the same period from the National Weather Service (NWS) site in Atlanta.

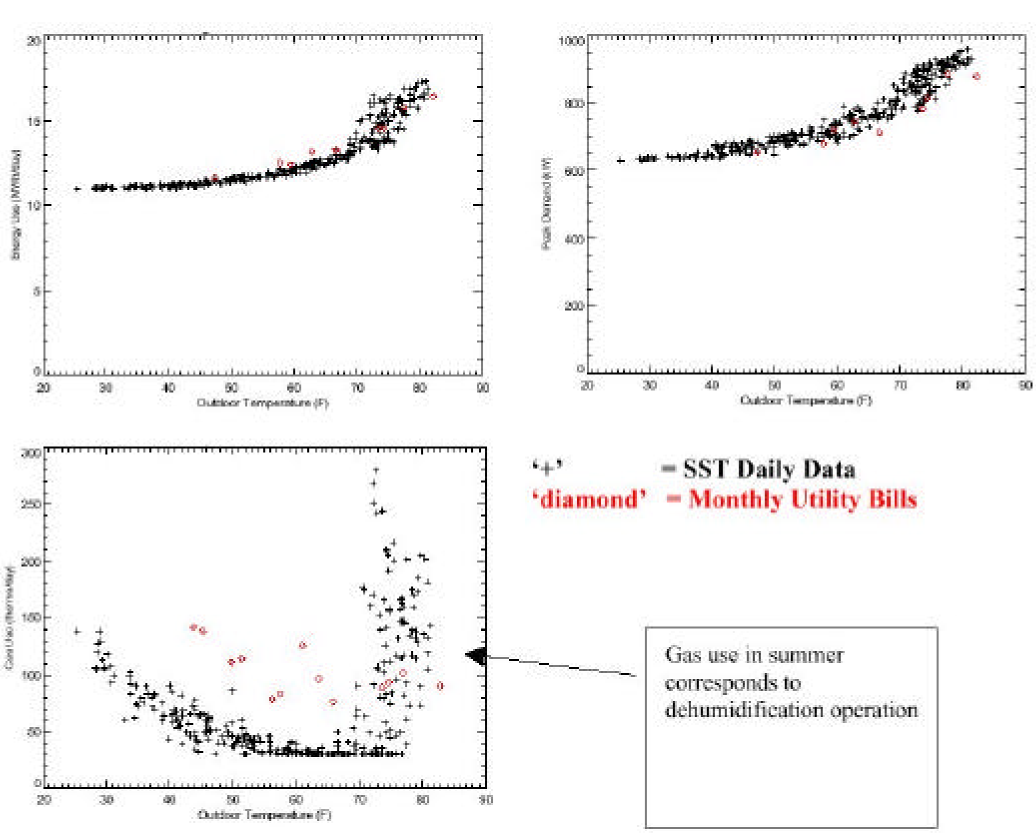

Figure 6. Comparing Daily Energy Use and Demand from SST to Utility Bills for Facility in Stone Mountain, Georgia.

The electric energy use and demand data from SST showed close agreement with the utility bill data. Both the base loads at low ambient temperatures and the temperature-dependent portion of the loads were in close agreement. Natural gas was used for both space heating and well as reheating for summertime dehumidification. The daily data from the model showed dehumidification was primarily required when daily average ambient temperatures were above 21°C [70°F]. However, the actual monthly gas use data showed a more uniform trend across the seasons.

Evaluating Efficiency Improvements

With the model shown to be representative of the actual base line facility, the next step was to evaluate the impact of various efficiency improvements. The first improvement was to change the minimum permissible condensing temperature set point. This is minimum set point is typically selected to ensure proper expansion valve and compressor operation. In the baseline store the condenser controls were somewhat arbitrarily set to maintain the condensing temperature at or above 27°C [80°F] on both the medium and low temperature racks. Figure 7 shows the annual energy savings that can be realized by lowering this value in three different climates. The impact is most pronounced at the higher temperatures. Lowering this set point has the most impact in the colder climate of Minneapolis, since ambient conditions are lower than this value for more hours of the year. As the set point continues to be lowered (on the low temperature racks only) annual energy use actually starts to increase slightly because the benefit of lower compressor energy use is offset by the long hours of condenser fan operation required to maintain these lower temperatures.

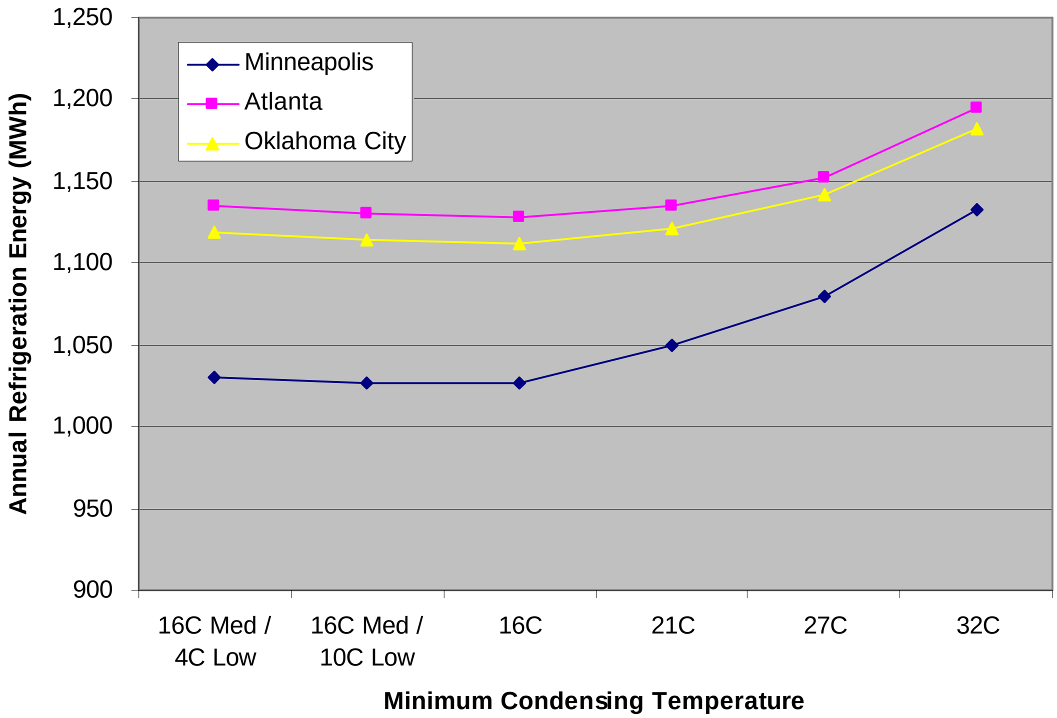

Figure 7. Impact of Minimum Condensing Temperature on Annual Energy Use

Another important control set point is the temperature of the liquid refrigerant maintained at the exit of the mechanical subcooler. Mechanical subcoolers are heat exchangers that use refrigeration effect from the medium temperature racks to provide subcooling on the low temperature racks. Mechanical subcooling is more efficient because every unit of cooling capacity provided to subcool liquid refrigerant results in an equal amount of low temperature capacity. Since the subcooler load is met with more-efficient medium temperature compressors, annual compressor energy use is decreased. Table 3 shows the savings that can be realized from providing even more mechanical subcooling than the set point of 24°C that is used at the base store. Dropping the delivered liquid temperature to 4°C would increase the savings to 27,200 kWh per year in this facility (compared to savings of 6,300 kWh at the 24°C control point). The on-peak demand would also decrease by 6 kW.

Table 3. Impact of Changing the Mechanical Subcooling Set Points

Liquid Temperature Set Point (°C)	Annual Energy Savings (kWh)	Peak Demand Savings (kW)
24 (base settings)	6,300	6.1
10	22,000	10.5
4	27,200	12

Note: All savings are relative to no mechanical subcooling

SST can also be used to show that the benefits of some technologies are highly dependent on the application details. The base store used traditional air-cooled condensers (see Figure 8, left). One improvement typically considered is to instead use an evaporative condenser than sprays water on the outside of prime-surface condenser tubes (Figure 8, right). This allows the refrigeration system to reject heat at the wet bulb temperature, which is often much lower than the dry bulb temperature. Evaporative condensers clearly offer the potential to lower the condensing temperature at design conditions and greatly reduce compressor power. However, the annual impact on energy use is less well understood.

Air-Cooled Condenser

Evaporatively-Cooled Condenser

Figure 8. Photos of Condensers Typically used in Supermarket Applications

Table 4 shows the annual impact of using an evaporative condenser instead of a traditional air-cooled condenser. Data are shown with three different minimum condensing temperatures. Surprisingly, the annual decrease in energy use is more modest than the peak demand reduction for Minneapolis. The annual energy savings range from 6,200 kWh at minimum condensing temperature of 16°C to 15,900 kWh at 27°C. Annual compressor energy use is actually higher for the evaporative condenser but the larger drop in condenser fan power results in net savings.

Table 4. Annual Savings From Using Evaporative- Instead of Air-Cooled Condensers in Minneapolis

	Minimum Condensing Temperature		
	16°C	**21°C**	**27°C**
Annual Reduction			
Operating Costs	$474	$721	$837
Compressor Energy (kWh)	(16,200)	(8,200)	(2,000)
Condenser Fan Energy (kWh)	22,400	20,900	17,900
Total Refrigeration Energy (kWh)	**6,200**	**12,800**	**15,900**
Total Refrigeration Demand (kW)	**7.9**	**7.9**	**7.9**
Saturated Condensing Temperature			
Annual Average - Rack A	1.2	0.9	0.5
Annual Average - Rack B	0.2	0.5	0.3
Annual Average - Rack C	(2.9)	(1.7)	(0.7)
Annual Average - Rack D	(1.2)	(0.5)	0.1
Maximum - Rack A	7.7	7.7	7.7
Maximum - Rack B	5.6	5.6	5.6
Maximum - Rack C	0.8	0.8	0.8
Maximum - Rack D	5.2	5.2	5.2

Notes: Evaporative condenser also includes a variable speed fan. Values in parentheses are negative.

The condensing temperatures in the table corroborate the energy and demand results. The peak condensing temperature at design conditions is typically 5 to 8°C lower for the four racks, which results in the demand savings of nearly 8 kW. However, the average condensing temperature is slightly higher on some racks, which drives the slight increase in compressor energy use.

These somewhat unexpected findings are a result of the climate and how supermarkets operated. Unlike refrigeration systems that operating primarily during the day to meet space conditioning loads, supermarket refrigeration systems operate 24 hours per day to meet the display case loads. A night, the wet bulb typically approaches the dry bulb temperature so there is little added performance benefit for the evaporative condenser. In fact at cooler ambient conditions when the wet and dry bulb are very close, the larger “approach” of the evaporative cooler (i.e., the difference between the condensing temperature and the ambient wet bulb) is actually a performance penalty.

Figure 9 shows that the benefits of using the evaporative condenser are greater in climates with more annual hours at summer time conditions (and a commensurately larger difference between the wet bulb and dry bulb temperatures). The highest savings occur with the drier climate conditions of Oklahoma City.

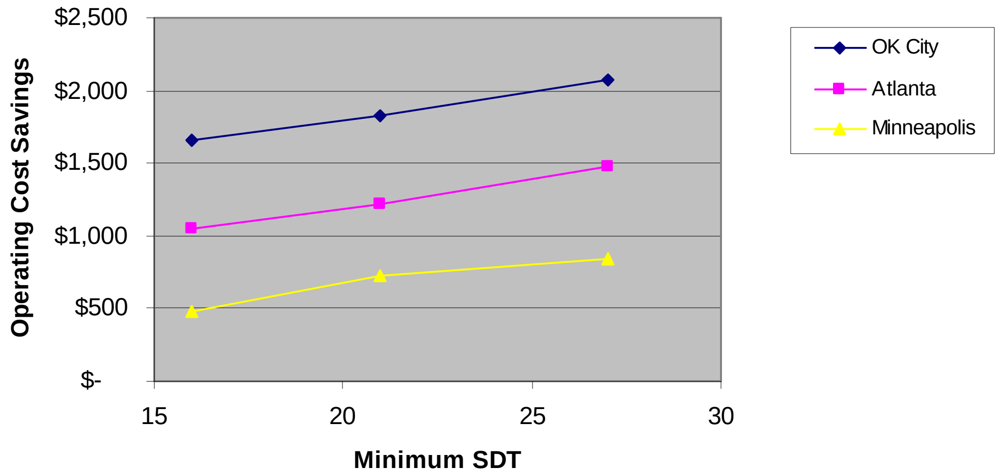

Figure 9. Comparing Evaporative Condenser Savings in Various Climates

The humidity dependence of refrigerated display case energy use is one of the most important examples of how the HVAC and refrigeration systems interact in a supermarket application. As more dehumidification is provided, refrigeration system energy use decreases. However, more HVAC operation (and energy use) is required to maintain lower space humidity levels. As a result any given facility will have an optimal humidity set point where total store energy use and operating costs are minimized.

Figure 10 and Table 5 show how HVAC and refrigeration system energy use vary as the dehumidification set points in the grocery and retail sales areas of the store are varied. Refrigeration system energy use drops because less anti-sweat heater operation is required, defrost cycles are shorter, and less moisture load is imposed on the display cases. However, HVAC energy increases because more reheat is required to prolong compressor operation and remove more moisture.

Table 5. Impact of Dehumidification Set Point on Supermarket Energy Use

	Dehumidification Set Point					
	7 g/kg	**8 g/kg**	**9 g/kg**	**10 g/kg**	**11 g/kg**	**12 g/kg**
Total Facility	4,736	4,648	4,620	4,617	4,616	4,616
Refrigeration	1,065	1,080	1,096	1,103	1,104	1,104
HVAC	855	751	708	697	697	697

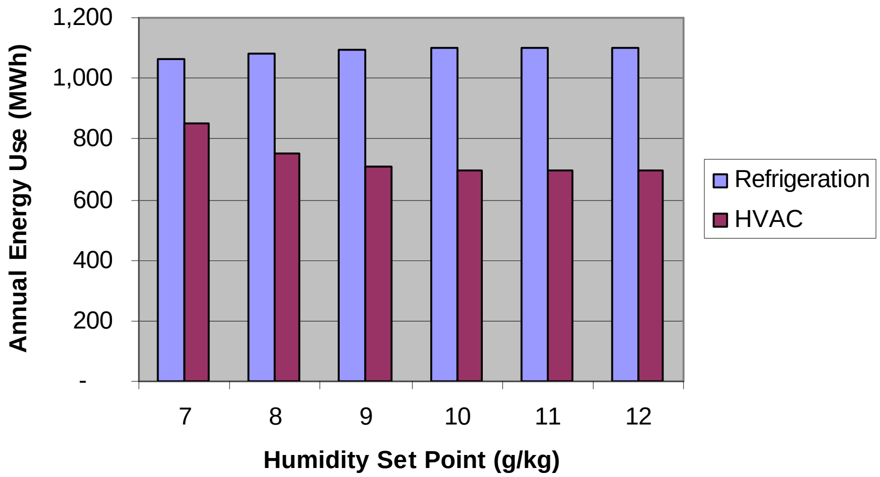

Figure 10. Impact of Dehumidification Set Point on Refrigeration and HVAC Energy Use

For the single-path HVAC system used in this case study, the added energy required by the HVAC system is more than the refrigeration savings, so overall costs are minimized with less dehumidification (and a higher humidity set point). For other HVAC systems with higher dehumidification efficiency – such as dual path or desiccant systems – the optimal dehumidification set point typically shifts to a lower value. To compare the performance of various HVAC systems, care must taken to first find the optimal operating point for each system (Henderson and Shirey 1996).

Conclusions

Supermarkets are complex facilities with significant interactions between the HVAC, refrigeration, and building envelope systems. SST has incorporated many of the necessary features into a single building simulation tool. By integrating detailed models of these systems into a Windows-based application, novice users can now easily evaluate several aspects of supermarket performance that were previously difficult to assess.

This paper has described the process of entering data for an actual supermarket, validating the model by comparing it to actual monthly energy use, and using the model to assess the impact of various control changes and efficiency improvements.

SST offers novice users the opportunity to evaluate and understand the complex interactions that have to this point been difficult to characterize.

References

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Henderson, H. and D. Shirey. '*Impacts of ASHRAE Standard 62-1989 on Florida Supermarkets,'* Final Report. Florida Solar Energy Center, Cape Canaveral. FSEC-CR-910-96. October 1996.