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Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Deliverable 2.5.6b

Evaluation of Energy Impact of Faults

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1.0 Introduction

Detecting HVAC system faults alerts operators of potential problems, and allows them to take appropriate action to resolve the system fault. Addressing the cause of the fault can be relatively low cost as in the case of a simple control change to restore proper schedules. However, elimination of other faults can be relatively expensive, especially those requiring substantial hardware replacements. An economic analysis would suggest that before repairing the fault, the cost of not repairing the fault would have to be greater than repairing the fault. The purpose of this activity is to evaluate the energy impacts of faults that are detected by the Project 2.5 Fault Detection software.

2.0 Analysis Methodology

The faults that are to be detected by the Fault Detection Software have been outlined in "Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics; Automated Diagnostics Software Requirements Specification, July 2002." These faults are reproduced in Table 1 below.

Table 1. Faults

Subsystem	Monitored Parameter	Fault Category	Fault
Chiller	Chilled Water Supply Temperature Maintenance	Chilled Water Supply Temperature not Maintained Correctly	The chilled water supply temperature is too high
			The chilled water supply temperature is too low
	Chiller Schedule	Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed	The chiller is on when it should be off. Energy is being wasted.
	Compressor Cycling	Compressor Cycling is Abnormal	The compressor is cycling on too frequently. It is not staying off for the minimum required off time.
			The compressor is cycling off too frequently. It is not staying on for the minimum required on time.
	Compressor and Condenser Fan Interlock (for air-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Fan	The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor
			The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.
	Compressor and Condenser Pump Interlock (for water-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Pump	The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor.
			The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump.
			The condenser pump is turning on too much in advance of the compressor and wasting energy.
Cooling Tower	Cooling Tower Fan Cycling	Cooling Tower Fan Cycling Problem	The cooling tower fan is not staying off long enough during cycling.
			The cooling tower fan is not staying on long enough during cycling.

Subsystem	Monitored Parameter	Fault Category	Fault
	Sump Temperature Control	Sump Temperature is Improperly Controlled	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.
			The cooling tower fan is on but it should be off. Energy is being wasted.
	Cooling Tower Approach	Cooling Tower Approach Problem	The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected.
	Cooling Tower Fan Staging	Cooling Tower Fan Staging Problem	The Sump temperature is above the cooling tower fan "on" set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.
			A fan is on even though the sump temperature is below the "off" set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.
	Cooling Tower Range	Cooling Tower Range Problem	The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity.
Chilled Water Loop	Supply Fan(s) and the Primary-Loop Chilled Water Pumps Interlock	Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly	The is possibly a problem with the supply fan control.
			This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.
	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps Interlocked	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly.	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.
			The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.
	Secondary and Primary Loop Chilled Water Pumps Interlock	Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.
Chiller / Cooling Tower	Cooling Tower Fan(s) and Condenser Pump Interlock	Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.
			The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case.

Subsystem	Monitored Parameter	Fault Category	Fault
Chiller / Water Loop	Compressor and Primary Chilled Water Pump(s) Interlock	Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly	The primary chilled water pumps are not interlocked properly with the compressor. The condenser pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump.
			The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result.
			The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.

The faults in Table 1 were reviewed to determine the following:

- Type of fault (time-based, schedule-based, temperature, cycling, etc.)
- Methods that could be used to calculate energy impact. The expected methods include DOE-2 simulations or simple algorithms.

The results of this review are shown in Table 2. The last column indicates if the impact of the fault will be analyzed, and the method that will be used for the analysis. In general, the faults fall into the following categories:

1. Schedule-based faults
2. Temperature-based faults
3. Cycling-based faults
4. Faults that do not have a significant energy impact, but do have an impact on equipment life.

Some of the faults listed in Table 2 do not, by themselves, have an energy impact. Some are better characterized as "diagnostic conditions." For example, the cooling tower approach, which is the difference between the sump temperature and the wet bulb temperature, will often be greater than the approach "benchmark," especially during low load or low ambient conditions. However, if the sump temperature is greater than the set point, then there will be an energy impact. The cooling tower approach, along with other variables, would be evaluated under these conditions to determine WHY the sump temperature is high.

Table 2. Fault Review

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
Chiller	Chilled Water Supply Temperature Maintenance	Chilled Water Supply Temperature not Maintained Correctly	The chilled water supply temperature is too high	Yes.	C-1
			The chilled water supply temperature is too low	Yes.	C-2

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
	Chiller Schedule	Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed	The chiller is on when it should be off. Energy is being wasted.	Yes.	C-3
	Compressor Cycling	Compressor Cycling is Abnormal	The compressor is cycling on too frequently. It is not staying off for the minimum required off time.	No. Cycling cannot be modeled	C-4
			The compressor is cycling off too frequently. It is not staying on for the minimum required on time.	No. Cycling cannot be modeled	C-5
	Compressor and Condenser Fan Interlock (for air-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Fan	The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor	No. Impacts equipment life, but has minimal energy impact.	C-6
			The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.	Yes.	C-7
	Compressor and Condenser Pump Interlock (for water-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Pump	The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor.	No. Impacts equipment life, but has minimal energy impact.	C-8
			The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump.	No. Cycling cannot be modeled	C-9
			The condenser pump is turning on too much in advance of the compressor and wasting energy.	Yes.	C-10
Cooling Tower	Cooling Tower Fan Cycling	Cooling Tower Fan Cycling Problem	The cooling tower fan is not staying off long enough during cycling.	No. Cycling cannot be modeled	CT-1
			The cooling tower fan is not staying on long enough during cycling.	No. Cycling cannot be modeled	CT-2
	Sump Temperature Control	Sump Temperature is Improperly Controlled	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.	Yes.	CT-3
			The cooling tower fan is on but it should be off. Energy is being wasted.	Yes	CT-4

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
	Cooling Tower Approach	Cooling Tower Approach Problem	The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected.	No. Approach will be greater than benchmark except during design conditions. This is a diagnostic that POINTS to a probable reduction in cooling tower capacity. Reduced cooling tower capacity is a major problem during high ambient conditions, but is a minor problem during low ambient conditions. During high ambient conditions, reduced CT capacity will cause higher than desired approach, which in turn will cause increased sump temperature, resulting in increased chiller electrical consumption.	CT-5
	Cooling Tower Fan Staging	Cooling Tower Fan Staging Problem	The Sump temperature is above the cooling tower fan "on" set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.	Yes.	CT-6
			A fan is on even though the sump temperature is below the "off" set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.	Yes.	CT-7
	Cooling Tower Range	Cooling Tower Range Problem	The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity.	No. Range will be less than benchmark except during high load conditions. The range will always be sufficient to reject all heat from the chiller. Because of this reason, this fault detection may not be useful for cooling tower diagnostics. Better to look at sump temperature first, and then if sump temperature is high, examine cooling tower fan operation and cooling tower approach.	CT-8
Chilled Water Loop	Supply Fan(s) and the Primary-Loop Chilled Water Pumps Interlock	Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly	There is possibly a problem with the supply fan control.		

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
			This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	Yes.	ChWL-1
	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps Interlocked	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly.	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.	Yes.	ChWL-2
			The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.	Yes.	ChWL-3
	Secondary and Primary Loop Chilled Water Pumps Interlock	Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	Yes.	ChWL-4
Chiller / Cooling Tower	Cooling Tower Fan(s) and Condenser Pump Interlock	Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.	Yes.	ChWL-5
			The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case.	No. Determining if the fan is not running when it should, is better handled by sump temperature control diagnostics. Determination of this impact is discussed elsewhere.	ChWL-6

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
Chiller / Water Loop	Compressor and Primary Chilled Water Pump(s) Interlock	Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly	The primary chilled water pumps are not interlocked properly with the compressor. The chilled water pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump.	No. Cycling cannot be modeled	ChWL-7
			The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result.	No. Cycling cannot be modeled	ChWL-8
			The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.	Yes.	ChWL-9

The impact of schedule-based faults can be evaluated through simple algorithms, while temperature-based faults require a simulation-based approach due to their interactive effects. The energy impacts of cycling-based faults and faults that have an impact on equipment life are difficult to assess through modeling or other techniques. The energy impacts of these faults will not be evaluated. A list of each fault and the calculation method is shown in Table 3 below.

Table 3. Impact Calculation Methodology Summary

#	Simulation, Algorithm, or None	Fault	Comments
C-1	DOE-2 Simulation	The chilled water supply temperature is too high	Impacts: Chiller and Cooling Tower energy consumption
C-2	DOE-2 Simulation	The chilled water supply temperature is too low	Impacts: Chiller and Cooling Tower energy consumption
C-3	Algorithm	The chiller is on when it should be off. Energy is being wasted.	Wasted chiller energy will be calculated for the time it was detected to be running unnecessarily.
C-7	Algorithm	The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.	Wasted condenser fan energy will be calculated for the time it was detected to be running unnecessarily
C-10	Algorithm	The condenser pump is turning on too much in advance of the compressor and wasting energy.	Wasted condenser pump energy will be calculated for the time it was detected to be running unnecessarily
CT-3	DOE-2 Simulation	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.	The IMPACT of improper sump temperature control will be simulated. There could be several CAUSES for improper sump temperature control, including CT fan being off or deteriorated capacity. Deteriorated capacity may be characterized by high approach temperatures at design conditions.

#	Simulation, Algorithm, or None	Fault	Comments
CT-4	DOE-2 Simulation	The cooling tower fan is on but it should be off. Energy is being wasted.	Yes The sump temperature is lower than the set point, and the fan is running unnecessarily.
CT-6	DOE-2 Simulation	The Sump temperature is above the cooling tower fan "on" set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.	Yes. Impact of increased sump temperature will be evaluated.
CT-7	DOE-2 Simulation	A fan is on even though the sump temperature is below the "off" set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.	Yes. Impact of decreased sump temperature will be evaluated. Impact of fans running when they should be off will be evaluated for the period that they were detected.
ChWL-1	Algorithm	This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	Primary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.
ChWL-2	Algorithm	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.	Secondary CHW pump energy will be calculated for the time it was detected to be running unnecessarily. However, if supply air temperature is cool enough, it is acceptable for supply fan to operate without secondary CHW pump.
ChWL-3	Algorithm	The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.	Secondary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.
ChWL-4	Algorithm	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	Secondary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.
ChWL-5	None	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.	Cooling tower fan energy will be calculated for the time it was detected to be running unnecessarily.

#	Simulation, Algorithm, or None	Fault	Comments
ChWL-9	Algorithm	The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.	Primary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.

3.0 Results

3.1 Simulation-based evaluation

A subset of building models from the California Statewide Building Efficiency Assessment (BEA) Study were selected to evaluate the effects of various operational changes. The following steps summarize the general procedure:

- Run base case to allow systems to self-size properly.
- Freeze capacities of all equipment.
- Change the selected parameter, e.g., chilled water supply temperature set point.
- Run model and extract monthly results.
- Normalize monthly results. The monthly results were normalized as shown below:

$$\text{Impact Factor (kWh/kWh - F)} = \frac{\text{Modified kWh - Baseline kWh}}{\text{Baseline kWh * Temp deviation(F)}}$$

The above procedure was applied to the building set, covering all of the California climate zones. The results have been plotted in the following figures as a function of monthly wet bulb temperature, which was a good indicator of load.

3.1.1 Chilled Water Supply Temperature Deviation

The chilled water supply temperature was varied above and below the baseline set point 1°F, 3°F, and 5°F. The impact factor is nearly constant at about 1.3 percent, as shown in Figure 1 and Figure 2.

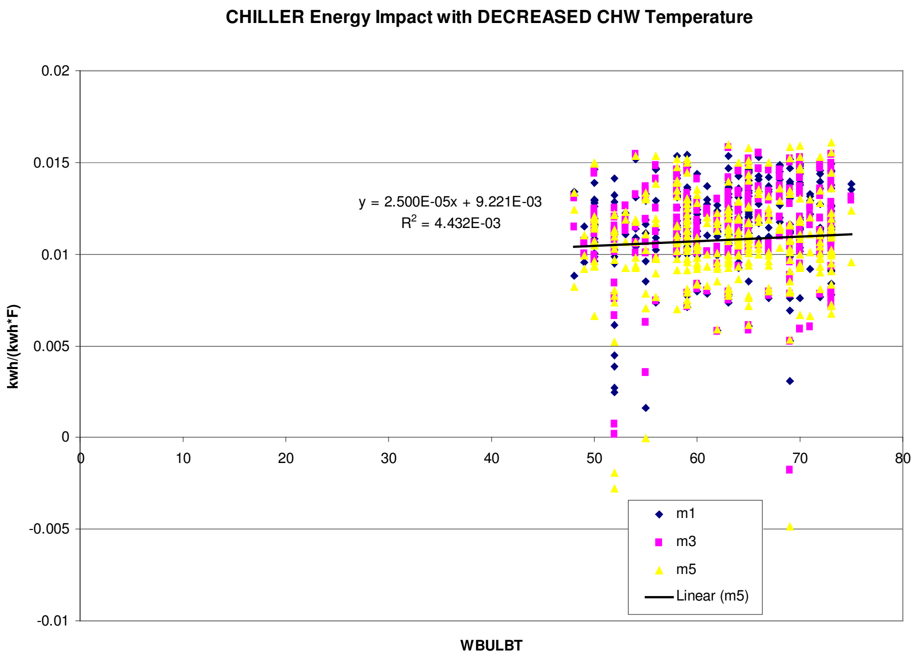

Figure 1. Monthly chiller energy impact with decreased chilled water temperature

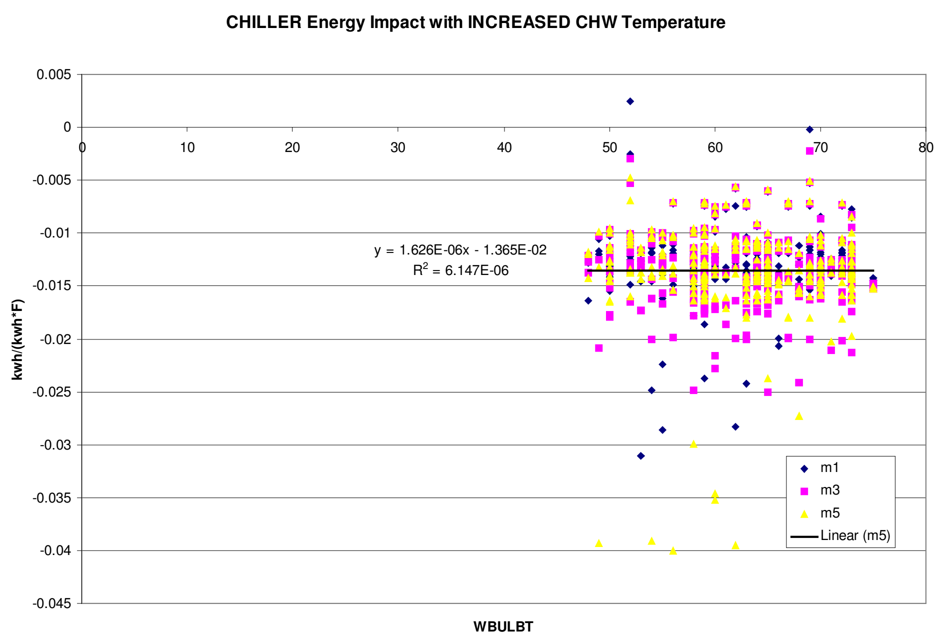

Figure 2. Monthly chiller energy impact with increased chilled water temperature

3.1.2 Cooling Tower Sump Temperature Deviation

To evaluate the effect of changes in the sump temperature on the chiller and cooling tower energy consumption, the cooling tower sump temperature set point was changed in the simulation models. The subsequent change in energy consumption provides an estimate of how changes in the cooling tower sump temperature will affect cooling energy consumption throughout the year.

In general, reducing the sump temperature set point reduces chiller energy consumption, but increases cooling tower fan energy. The effects are greatest at low wet bulb temperatures, and smallest at high wet bulb temperatures. The reason for this is that at low wet bulb temperatures, the cooling tower normally has excess capacity, and it is possible to reduce the sump temperature. Decreasing the sump temperature set point will increase the cooling tower fan operation, which will subsequently reduce the sump temperature and decrease the chiller energy consumption.

At higher wet bulb temperatures, the effects are not as pronounced. The reason for this is that there is less cooling tower capacity available to decrease the sump temperature because the cooling tower fans are already operating at a higher duty cycle. Decreasing the sump temperature set point will further increase the fan operation, but the percentage increase is not as great. Furthermore, the actual sump temperature may not reach the set point since the increased ambient wet bulb temperature may be too high, even at the minimum approach delta temperature.

As the temperature entering the chiller condenser decreases, the energy consumption of the chiller decreases. The impact factor is somewhat correlated with the monthly average wet bulb temperature, as shown in Figure 3 through Figure 6. The results are summarized in Table 4.

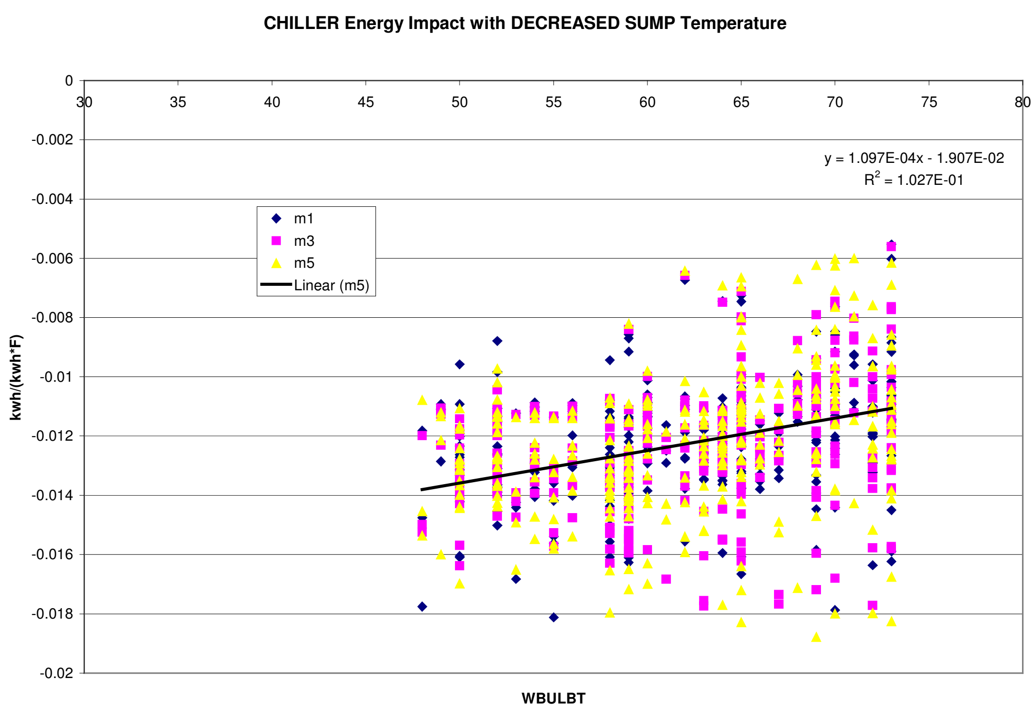

Figure 3. Monthly chiller energy impact with decreased cooling tower sump temperature

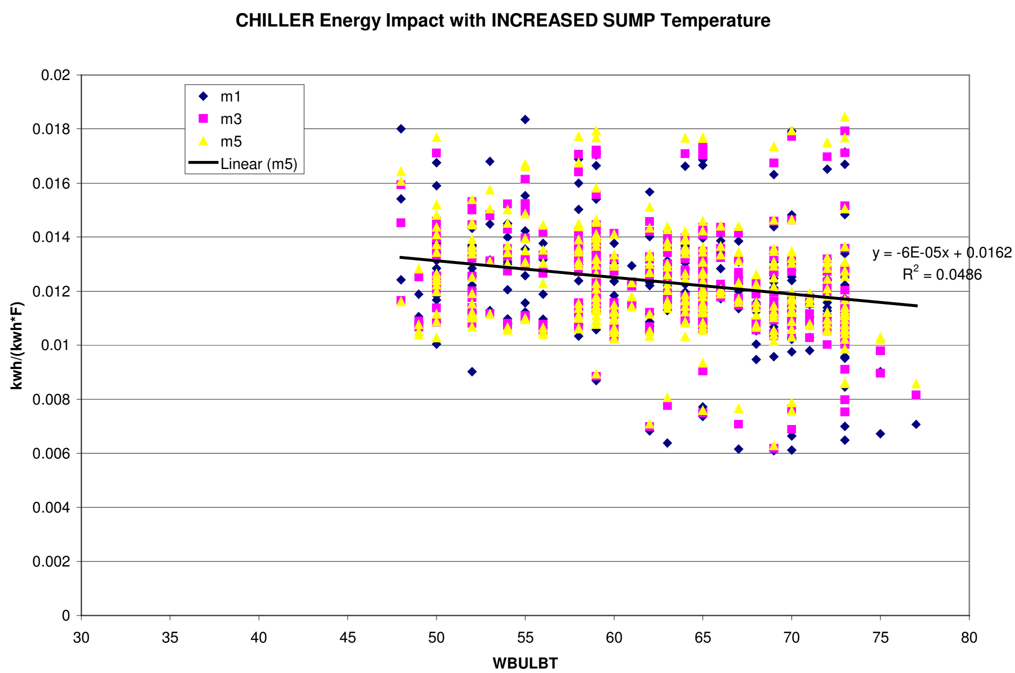

Figure 4. Monthly chiller energy impact with increased cooling tower sump temperature

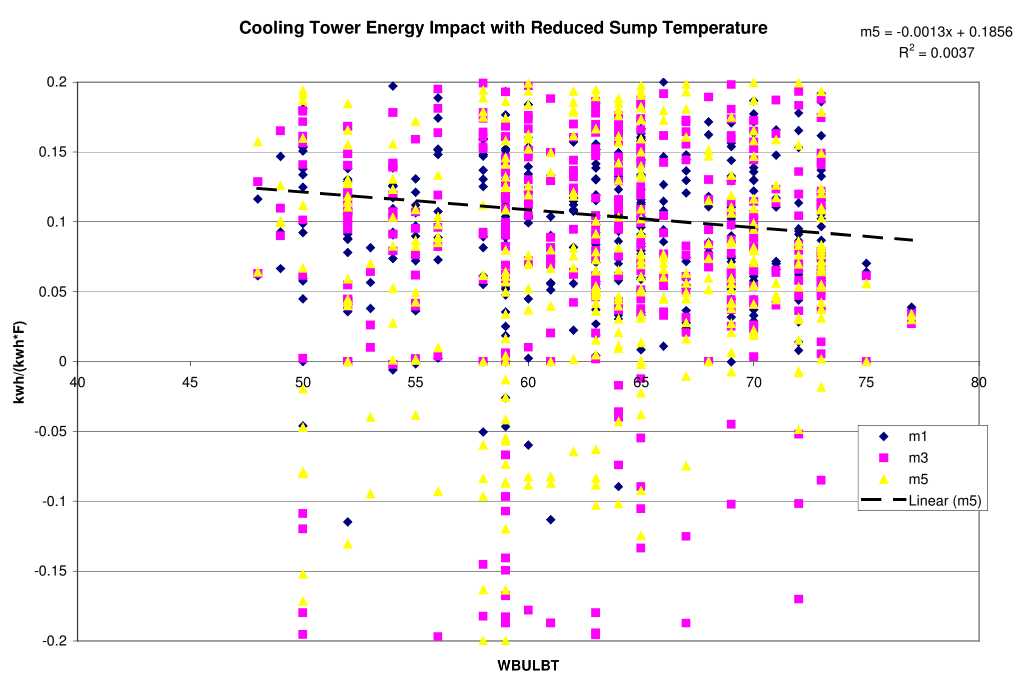

Figure 5. Monthly cooling tower fan energy impact with decreased cooling tower sump temperature

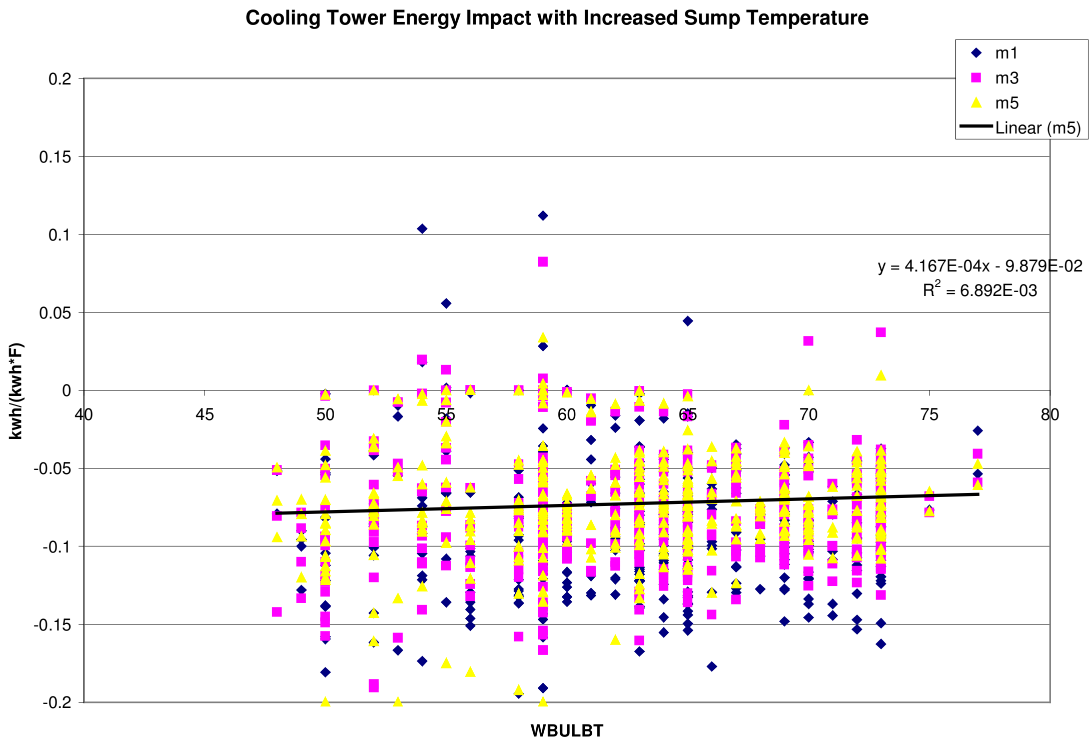

Figure 6. Monthly cooling tower fan energy impact with increased cooling tower sump temperature

Table 4. Summary of Simulation-based Impact Factors

Fault ID	Description	End Use	Slope	Constant
C-1*	CHW Supply Temperature Greater than set point	Chiller	0	-0.0132
C-2*	CHW Supply Temperature Less than set point	Chiller	0	0.0113
CT-4	Cooling Tower Sump Temperature less than set point	Chiller	.000110	-.0191
		Cooling Tower Fan	-0.0013	0.186
CT-3	Cooling Tower Sump Temperature greater than set point	Chiller	-.0000617	.0162
		Cooling Tower Fan	.000417	- .0988

*Cooling Tower energy consumption impact was negligible

3.1.3 Using the simulation results to calculate energy impact

The impacts in the previous section, summarized in Table 4, can be used to calculate energy impacts using a minimum number of variables. As shown in the table, energy impacts can be calculated for chilled water supply temperature greater or less than the set point, and Cooling Tower sump temperature greater or less than the set point. As shown in the figures in the preceding section, the effect on energy consumption is weakly correlated with the ambient wet bulb temperature.

To apply these impacts, the following inputs are required:

- Energy consumption for the period that the temperature deviated from set point.
- Magnitude of temperature deviation, i.e., the difference between the observed and desired temperature for either the chilled water supply temperature or the cooling tower sump temperature.
- Ambient wet bulb temperature for the period being evaluated.

The evaluation period should be no less than one day, and no more than one month.

For calculating a daily impact, the procedure is as follows

1. Select the applicable Fault ID
2. If necessary, determine the daily average wet bulb temperature.
3. Determine the magnitude of the temperature deviation
4. Determine the daily energy consumption of the end use.
5. Calculate the energy impact using the following formulas.

$$E_{Impact} = E_{measured} * F * DT$$

$$Where:$$

$$E_{Impact} = Energy\ consumption\ impact\ (kWh)$$

$$E_{measured} = Measured\ energy\ consumption\ for\ period\ (kWh)$$

$$F = Impact\ Factor = Constant * Slope * T_{WB}$$

$$Constant\ from\ Table\ 4$$

$$Slope\ from\ Table\ 4$$

$$T_{WB} = Wet\ Bulb\ Temperature\ for\ the\ period\ under\ consideration, i.e., day, week, month\ (°F)$$

$$DT = Deviation\ between\ desired\ and\ observed\ temperature\ (°F)$$

3.2 Algorithm-based results

Nearly all of the algorithm-based results are associated with components or systems that are operating longer than is required. The general form of the algorithm is:

Daily Energy Impact = daily hours of excess usage * equipment electrical demand

Required Inputs:

- Period that fault has existed
- Equipment electrical demand (name plate or monitored value)

Table 5 lists each of the algorithm-based impacts, a description of the fault, and the method to use to determine the Time and Demand to use in the above equation.

Table 5. Algorithm-based impacts

#	Fault	Time (hr)	Demand (kW)
C-3	The chiller is on when it should be off.	(Daily scheduled operating time) – (actual daily operating time)	Average measured demand over period of excess chiller run time
C-7	The condenser fan is on while the compressor is off.	(Daily fan run time) – (daily compressor run time)	Measured fan demand. If not available, use nameplate demand
C-10	The condenser pump is turning on too much in advance of the compressor.	(Daily condenser pump run time – Daily compressor run time – (Number of times compressor cycled on in day)* (condenser pump time delay)	Measured pump demand. If not available, use nameplate demand
ChWL-1	This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	(Daily CHW pump run time) – (Daily supply fan run time)	Measured CHW pump demand. If not available, use nameplate demand.
ChWL-3	The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply fans it serves are off.	(Daily secondary CHW pump run time) – (Daily supply fan run time)	Measured secondary CHW pump electrical demand. If not available, use nameplate demand. Note: If VSD is used, measured fan demand must be used.
ChWL-4	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	(Daily secondary CHW pump run time) – (Daily primary CHW pump run time)	Measured secondary CHW pump electrical demand. If not available, use nameplate demand. Note: If VSD is used, measured fan demand must be used.
ChWL-9	The compressor is not properly interlocked with the primary chilled water pumps. The primary chilled water pumps are cycling on too much in advance of the compressor.	(Daily primary CHW pump run time – Daily compressor run time – (Number of times compressor cycled on in day)* (primary CHW pump time delay)	Measured primary CHW pump electrical demand. If not available, use nameplate demand. Note: If VSD is used, measured fan demand must be used.

4.0 Discussion and Conclusions

The previous sections have provided a way of calculating the impacts associated with various faults. Most of the faults are non-interactive, or directly sum with the impacts of other faults, i.e., when multiple components are operating unnecessarily, their energy impacts all increase the overall consumption of the building. However, temperature related faults can have inverse impacts, i.e., lowering the cooling tower sump temperature will increase cooling tower fan energy consumption, but decrease chiller energy consumption. This section examines the relative impacts of the faults evaluated in the previous sections.

Table 6 lists typical electrical demands for the chiller, cooling tower, and associated circulation pumps for a 250,000 square foot office building. These values will be used to calculate the relative impacts of these faults.

Table 6. High-rise office building cooling plant electrical demand

End Use	Demand (kW)	Normalized Demand (W/SF)	Normalized Demand (kW/ton)	Percent of Total Demand (%)
Chiller (620 tons)	420.49	1.68	0.68	83%
Cooling Tower Fan	27.55	0.11	0.04	5%
Chilled Water Pumps	31.57	0.13	0.05	6%
Condenser Water Pumps	25.77	0.10	0.04	5%
Total	505.38	2.02	0.81	100%

Since impacts associated with the chiller and cooling tower are interactive, their overall impact should be evaluated. For example, faults CT-3 and CT-4 are associated with the cooling tower sump temperature being above or below the set point. If the sump temperature is above the set point, the cooling tower fan energy is reduced, but the chiller energy is increased.

Table 7 lists the magnitude of the temperature-related impacts for a one degree variation in the subject temperature. For example, if the CHW supply temperature is lower than the CHW set point by 1° F (fault C-2), the average demand of the entire cooling plant (the sum of the chiller, cooling tower fans, and circulation pumps) will increase by 0.94 percent.

The impacts for faults CT-3 and CT-4 illustrate the interactive effects of changes in the cooling tower sump temperature. Over a wide range of ambient wet bulb temperature, every one degree Fahrenheit increase in the cooling tower sump temperature results in a net demand increase of the chiller plus the cooling tower fans of 0.6 percent. Since these impacts are dependent on the average wet bulb temperature, the results are also shown in Figure 7.

Table 7. Magnitude of Electrical Impact

Fault ID	Description	End Use	Average Chiller Impact (kW/ton)	Average Cooling Tower Fan Impact (kW/ton-°F)	Average Net Impact (kW/ton-°F)	Average Percent of Net Cooling Plant Demand
C-1	CHW Supply Temperature greater than set point	Chiller	-0.009		**-0.009**	**-1.10%**
C-2	CHW Supply Temperature less than set point	Chiller	0.008		**0.008**	**0.94%**
CT-3	Cooling Tower Sump Temperature greater than set point	Chiller	0.008			
		Cooling Tower Fan		-0.003	**0.005**	**0.63%**
CT-4	Cooling Tower Sump Temperature less than set point	Chiller	-0.008			
		Cooling Tower Fan		0.005	**-0.004**	**-0.45%**

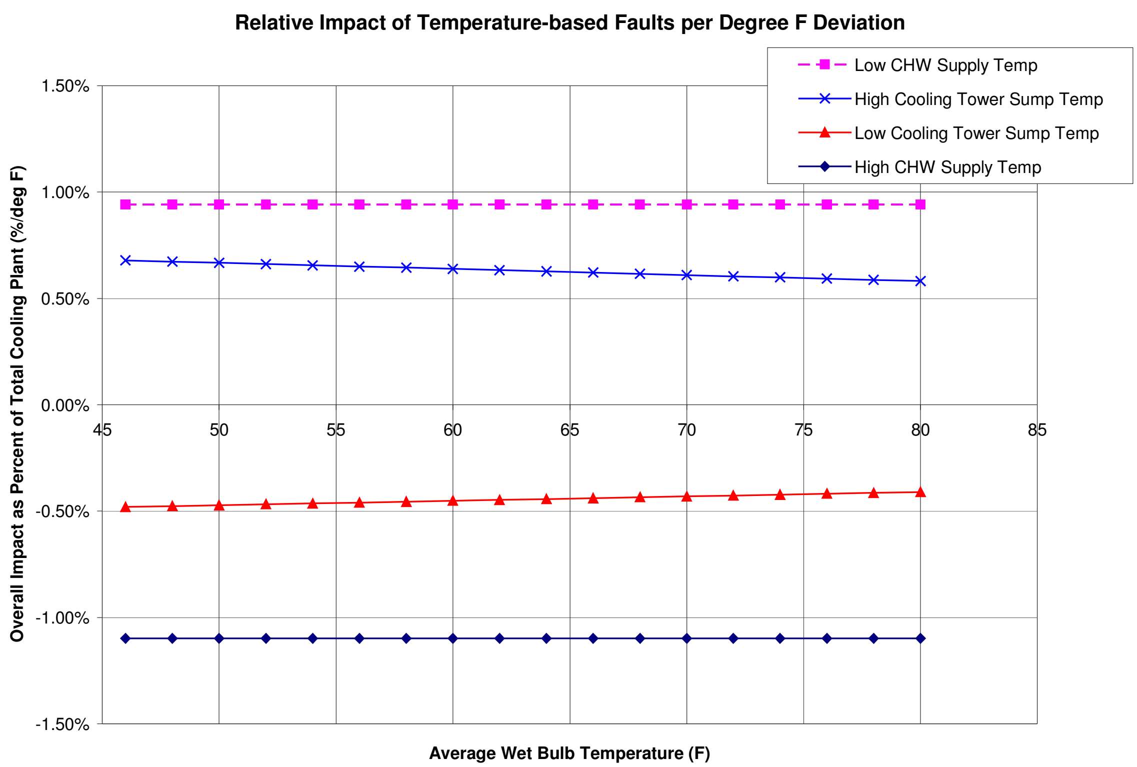

Figure 7. Relative impact of temperature-based faults

Some so-called faults can actually decrease energy consumption. If the sump temperature is lower than the set point (Fault CT-4), the net result is a reduction in overall consumption. Similarly, increasing the CHW supply temperature (Fault C-1) can also reduce energy consumption for the cooling plant. However, increasing the CHW supply temperature could have undesired effects such as less effective humidity control and potential increases in supply fan energy consumption, which were not the subject of this study.

Other faults are associated with equipment running longer than necessary. These are shown in Table 8, along with the temperature-related impacts shown above, but for a 4°F temperature deviation. The impact associated with equipment running longer than necessary is very significant. For example, the impact of excess chiller operation is on the order of 20 times greater than an increase in the cooling tower sump temperature of 4°F, for the same time period. Unnecessary pump and fan operation is also greater than any of the temperature-related faults.

Table 8. Relative impacts

#	Fault	Energy Consumption for one hour of fault operation (kWh/ton)
C-3	Chiller running longer than necessary	0.68
C-7	The condenser fan running unnecessarily.	0.08
C-10	Condenser pump turning on too early and running unnecessarily.	0.04
ChWL-1 ChWl-9	This chilled water pump is being operated unnecessarily	0.05
ChWL-3 ChWL-4	The secondary chilled water pump is operating unnecessarily when all supply fans it serves are off.	0.05
C-1	CHW Supply Temperature 4°F greater than set point	-0.036
C-2	CHW Supply Temperature 4°F less than set point	0.032
CT-3	Cooling Tower Sump Temperature 4 °F greater than set point	0.020
CT-4	Cooling Tower Sump Temperature 4 °F less than set point	-0.016

Although the magnitude of one hour of unnecessary equipment operation is greater than the magnitude of one hour of any of the temperature-related faults, it isn't clear that both of these fault categories would exist for the same length of time. It is possible that the temperature-related faults could exist for a much longer period of time since they are more subtle; equipment running when it isn't supposed to be on is more likely to be noticed than increased sump temperature that can quietly exist for weeks, if not years. With this in mind, the long-term benefits of identifying and correcting temperature-based faults can be as significant, or potentially more significant, than detecting unnecessary equipment operation.