Chiller Start/Stop Optimization for a Campus-wide Chilled Water System With a Thermal Storage Tank Under a Four-Period Electricity Rate Schedule

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ABSTRACT

The existence of a 1.4-million-gallon chilled water thermal storage tank greatly increases the operational flexibility of a campus-wide chilled water system under a four-part electricity rate structure. While significant operational savings can be expected, the complication in the rate structure also requires more involved control over the tank charging and discharging processes.

A chiller start-stop optimization program has been developed and implemented into the Energy Management and Control System (EMCS) to determine the number of chillers that need to be brought on line and the start and stop times for each chiller daily, based on the prediction of the campus cooling load within the coming 24 hours. With timely and accurate weather forecasting, the actual tank charging and discharging process closely matches the simulation.

INTRODUCTION

Texas A&M University - Corpus Christ (TAMUCC) has over one million square feet of conditioned space, including more than a dozen buildings housing classrooms, laboratories, offices, student service centers, library, gyms and other research facilities. The entire campus's peak cooling load is estimated at around 1,800 ton. Three 1000-ton centrifugal chillers located at the central plant supply chilled water to the campus. Under design conditions, each chiller supplies approximately 1,700 gpm of chilled water at 42 °F, with return water temperature of 56 °F. The chilled water system is a typical primary-secondary loop configuration with constant-speed primary pumps and variable-speed secondary pumps. The thermal storage tank is situated on the floating bypass, as shown in Figure 1.

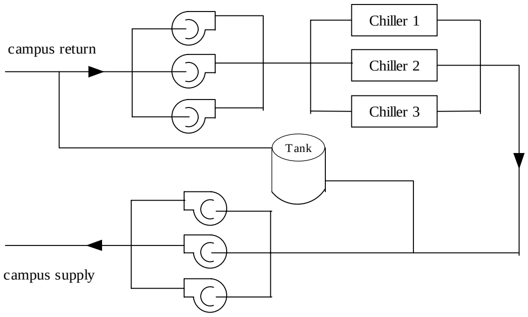

Figure 1. Central plant chilled water loop and the thermal storage tank

The thermal storage tank is 64 feet tall and 61 feet in diameter with a total volume capacity of 1,400,000 gallon (Figure 2). Under design conditions, the full tank of 42 °F chilled water is equivalent to a cooling capacity of 12,000 ton-hour. The temperatures of the stratified chilled water layers are monitored by 30 temperature sensors evenly distributed along the vertical dimension of the tank. Without any additional control, the thermal storage tank acts much like a natural reservoir – it charges when the total chiller production exceeds the chilled water demand by the campus, and discharges when the production is less than the demand.

Figure 2. The thermal storage tank

TAMUCC's original utility rate was a two-price only (on-peak and off-peak) structure with demand charges. The thermal storage was charged during the off-peak period and discharged during the on-peak period (from 1 to 7 p.m.). The control system had no direct control over the tank charging-discharging process. The number of chillers to be activated and the start-stop times for all chillers are largely determined from plant operators' experience.

From the beginning of the year 2002, a four-part utility rate structure offered by another utility company was accepted by the university, against several other competitive offers, including a normalized flat rate schedule. The new multiple-tiered rate structure is considered to be favorable to the university in terms of operating costs compared to other potential rate structures, but only if the chillers and the thermal storage system can be operated in the most efficient way to take full advantage of the new rate structure. The new rate structure is divided into four parts, with each part covering several months (Table 1). April, October and November are charged for the lowest electricity price any time of the day. From December to March, two prices are included in the rate schedule. May and September are charged for three electricity prices at different time of day. The peak summer period from June to August has the most complicated rate schedule, which includes all the four electricity prices. Except April, October and November, weekends have different rate schedules from weekdays of the same month. The average electricity price of this four-part rate structure is supposed to be cheaper comparing to a flat rate of $0.0383/kWh, which is being offered to many other campuses within the university system.

Table 1. Four-price electricity rate schedule

TIME	DEC-MAR		APR, OCT, NOV		MAY & SEP		JUN - AUG	
	M–F (*)	SS (**)	M -F	SS	M -F	SS	M -F	SS
0:00	1	1	1	1	1	1	1	1
1:00	1	1	1	1	1	1	1	1
2:00	1	1	1	1	1	1	1	1
3:00	1	1	1	1	1	1	1	1
4:00	1	1	1	1	1	1	1	1
5:00	1	1	1	1	1	1	1	1
6:00	2	1	1	1	1	1	1	1
7:00	2	1	1	1	1	1	1	1
8:00	2	1	1	1	1	1	2	1
9:00	2	1	1	1	1	1	2	1
10:00	2	1	1	1	2	1	3	2
11:00	2	1	1	1	2	1	3	2
12:00	1	1	1	1	2	1	3	2
13:00	1	1	1	1	2	1	3	2
14:00	1	1	1	1	3	2	4	3
15:00	1	1	1	1	3	2	4	3
16:00	1	1	1	1	3	2	4	3
17:00	1	1	1	1	3	2	4	3
18:00	2	1	1	1	3	2	4	3
19:00	2	1	1	1	3	2	4	3
20:00	2	1	1	1	2	2	3	3
21:00	2	1	1	1	2	2	3	3
22:00	1	1	1	1	1	1	2	2
23:00	1	1	1	1	1	1	2	2

Price	1	Lowest
	2	
	3	
	4	Highest

(* Monday - Friday; ** Saturday and Sunday)

For the cooler 7 months, i.e., October to April, the operation of the chilled water system is relatively easy compared to the remaining warm weather months. Since only the lowest price is involved in the rate structure for April, October, and November and the weekends of all the 7 months, there is essentially no need to control tank charging and discharging. However, due to the inevitable heat loss from the thermal storage tank, albeit small, the storage in the tank should be kept at the minimum level. For the weekdays of the months from December to March, since the two price-2 periods are separated by 6 hours of price-1 period, there is practically no difficulty in avoiding running chillers during the price-2 periods.

The situation is much more complicated for the remaining warm months. For most of the days during these months, the thermal storage tank, when fully charged, is able to provide enough chilled water to cover the highest-price period (i.e., 6 hours for the weekdays and 8 hours for the weekends) by itself. After that, the tank may still have enough chilled water left to provide cooling to the campus for up to several hours, depending on the day's actual cooling load. The chillers should be brought on timely before the tank is depleted to meet the campus's cooling demand; meanwhile, they should also be stopped in time to avoid running into higher-price time periods. The tank should be charged to certain level so that it can provide chilled water for as many high-price hours as possible; meanwhile, it is not always desirable to have a full tank if the campus load is relatively low. The number of chillers should be used during the charging cycle, the exact times to start and stop a specific chiller shall be determined accurately to take full advantage of the four-part rate structure instead of being penalized otherwise.

The chillers start stop optimization program discussed in this paper is dedicated for the summer months from May to September.

PROCEDURES TO OPTIMIZE CHILLER STARTS AND STOPS

Generally speaking, for the months from May to September, the tank should be charged overnight when the electricity price is relatively low and discharged in the afternoon when the electricity price is relatively high. Assume the tank is almost depleted at 10 p.m., and one or more chillers are turned on in sequence. If the chillers produce more cooling than demanded by the campus at the time, the tank will be gradually charged. The tank is fully charged sometime in the early afternoon, right before the most expensive price period starts. Then all the chillers are shut down and the tank starts to discharge. A new tank charging-discharging cycle starts when the thermal storage tank is depleted (or almost depleted).

This conceptual tank charging-discharging sequence is not difficult to grasp. However, the exact times for starting and stopping the chillers that will maximize the usage of the tank during high price hours can only be determined from more detailed analysis. The optimal chiller start stop sequence varies from day to day depending on the campus' actual cooling load. The chiller start-stop optimization program was developed and implemented into the EMCS control system to automate this decision-making process every day.

The procedures of the chiller start stop optimization include the following steps. First, the cooling load of the campus is estimated for the next 24 hours with a load prediction model based on weather forecast. Next, the exact period of time for the tank to discharge is selected, which automatically determines the time period to charge the tank. The average chiller production rate required for the charging period is calculated with the total estimated campus load and the available charging hours. After that, the number of chillers to be turned on and the runtimes for each chiller is determined based on the predicted campus load. Finally, the start-stop times for each chiller are scheduled precisely, after taking many restrictions and specific requirements into consideration.

CAMPUS LOAD PREDICTION MODEL

The campus' cooling load is regarded as a simple function of the outside air temperature. The load model could have been created from the total chilled water consumption data trended at the central plant, i.e., the chilled water flow, the supply and the return temperatures. Unfortunately, the chilled water flow sensor is not working properly, therefore there is no direct means to measure the campus chilled water consumption.

The chilled water supplied to the campus came from two sources, the chillers and/or the thermal storage tank. When the chillers produce more than needed, the excess chilled water flows through the tank and charges it; when chillers produce less than needed, the tank discharges to help meet the demand; when all chillers are shut down, the tank provides all the needed chilled water to the campus. Under the last scenario, the campus' cooling load can be evaluated from the tank's discharging rate. The rate at which the tank discharges (or is being charged) can be determined by comparing the average chilled water temperatures inside the tank within a certain period of time.

Figure 3 and Figure 4 show the historical thermal storage tank's discharging (or charging) rate for weekdays and weekends respectively. A positive value indicates the tank was discharging and a negative value indicates the tank was being charged. For both figures, clear separations among data are displayed. The top cloud of data shows the operation scenario when all chillers were shut down and the campus load was solely supplied by the tank itself, therefore discharging rates are all positive; the middle cloud of data shows the operation scenario when one chiller was running and the tank may discharge or be charged depending on the campus load; Similarly, the bottom cloud of data was for the operation scenario when two chillers were running, and the tank would always be charged since the campus load never exceeded the capacity of two fully loaded chillers.

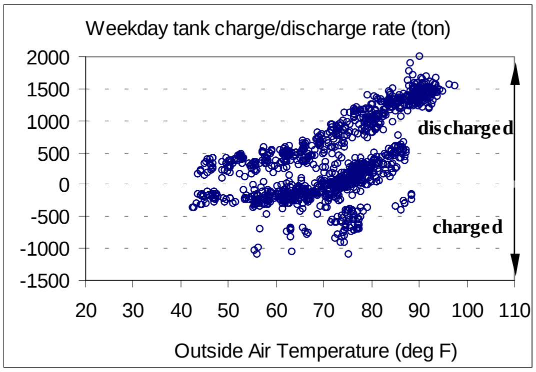

Figure 3. Thermal storage tank charge/discharge rate (weekdays)

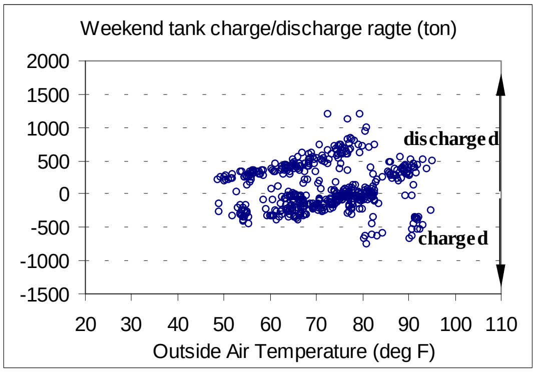

Figure 4. Thermal storage tank charge/discharge rate (weekends)

The campus load for both weekdays and weekends can be determined from the two figures by looking at the top portions of data. Since no chiller was running at those times, the rates at which the tank discharges were exactly what the campus needed at the time. For simplicity, the campus' cooling loads are simulated with simple three-point-change-point (3PCP) linear models for both the weekdays and the weekends, as shown in Figure 5. With the load models created, hour-by-hour campus loads for the next 24 hours can be estimated with the predicted outside air temperatures.

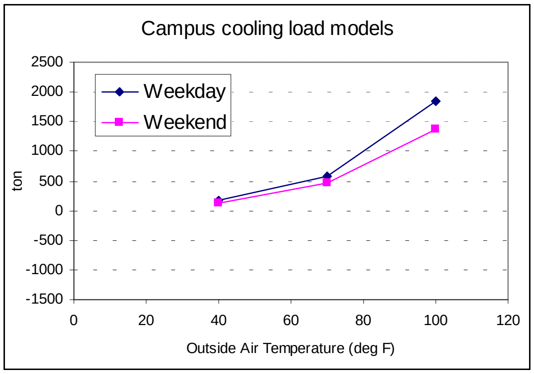

Figure 5. Campus cooling load models

The outside air temperature (OAT) profile for the next 24 hours is generated from the weather channel's daily weather forecast. For simplicity, only the daytime high and the overnight low temperatures are taken as the inputs to the program. The temperature profile is generated with a sine function, which peaks at 3 p.m. and bottoms at 3 a.m. The predicted OAT at any hour (T_n) is calculated as

$$T_n = \frac{T_{hi} + T_{lo}}{2} + \frac{T_{hi} - T_{lo}}{2} \times Sin(\frac{n-9}{12} \times \pi)$$

Figure 6 shows the comparison between the generated OAT profile and the actual hour-by-hour forecast from the weather channel. The close match between the two indicates the generated OAT profile is sufficiently accurate.

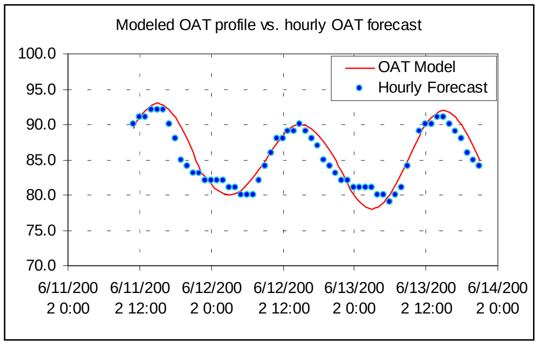

Figure 6. Modeled OAT profile vs. hourly OAT forecast from weather channel

TANK CHARGE/DISCHARGE PERIODS

With the campus load predicted for the next 24 hours, the discharging period for the thermal storage tank can be selected. Naturally, it is desirable to use the chilled water storage in the tank instead of chillers' production for as many hours as possible during the higher-price periods.

For all the weekdays from May to September, the highest-price (price-4) period starts at 14:00 and ends at 20:00. Since the thermal storage tank has a capacity of around 12,000 ton-hr and the campus's peak cooling load is known to be around 1,800 ton, it is certain that the campus can solely depend on the tank without running any chiller for the 6 hour of the highest-price period, provided the tank is fully charged before discharging, and chilled water returns at the designed temperature. After that, if the tank still has a certain amount of usable chilled water left, the remaining chilled water in the tank should be used on the hours selected from the second most expensive period, i.e., from 20:00 to 22:00, and then 14:00 back to 10:00.

For the rare cases, the tank may still have chilled water left after supplying the campus for the most expensive 12 hours. What to do next depends on the month. For May and September, since all the rest of hours are charged for the cheapest rate (price-1), the tank should be charged only to the total amount predicted for the most expensive 12 hours. The tank should start discharging on 10:00 and start the charging process on 22:00. For June, July and August, however, the tank should be exploited further. There is another 4 hours (8:00, 9:00, 22:00, 23:00) of price-2 period that can take advantage of the thermal storage tank. The tank discharging period is determined from the hours selected in that manner. The discharging process starts at the earliest selected hour and ends at the latest selected hour.

The weekends are a little different from the weekdays due to the difference in rate schedules. For May and September, only 8 hours from 14:00 to 22:00 are charged for price-2 and all other hours are charged for price-1. The tank should only be charged to the amount required by the 8 more expensive hours. The weekends of June, July and August are charged for three prices daily, therefore similar method as described for the weekdays should be used to determine the time period for the tank discharging process.

The tank charging process starts as soon as the tank discharging process is over, when the tank is expected to be depleted (or almost depleted). Due to the fact that the physical plant requires the chillers to be started under operators' observation, the actual tank charging process should be started before the operator on the last shift leaves duty, which is around 22:30. For that reason, the latest time to stop the tank discharging cycle (and to start the tank charging cycle) has been set at 22:00. The tank charging cycle ends at the start of the tank discharging cycle.

TOTAL PREDICTED CHILLER LOAD AND CHILLER RUNTIME

The total predicted chiller load (L_p) is defined as the load seen by all the chillers for the next charging cycle, which is essentially the total estimated campus load (Lc) for the next 24 hours, unless the tank is not depleted at the start of the charging cycle. In that case, the total predicted chiller load is the estimated total campus load less the remaining cooling tonnage in the tank.

Having known the total estimated chiller load and the length of the tank-charging period (H_{chg}), the average chiller load during the tank charging cycle can be determined as

$$R_p = \frac{L_p}{H_{chg}}$$

And the total chiller runtime can be calculated as

$$H_{tot} = \frac{L_p}{C_{chlr}}$$

, where C_{chlr} stands for single chiller's capacity. Depending on the average chiller load, one, two or all three chillers may need to be turned on during the charging cycle.

CHILLER START/STOP OPTIMIZATION

If R_p is greater than two chillers' capacity, two (the lead and the lag) chillers will need to run for the entire charging period, and the third chiller (the backup) also needs to run for certain period of time. The runtime for the backup chiller is calculated as

$$H_{bak} = H_{tot} - 2 \times H_{chg}$$

The chiller start/stop sequence is determined as:

- Both the lead and the lag chillers will be turned on at the start of the tank charging cycle (T_{cs}), and shut down at the end of the tank charging cycle, or the start of the tank discharging cycle (T_{ds});

- The backup chiller starts at T_{cs}, and stops at $T_{cs} + H_{bak}$.

If Rp is smaller than one chiller's capacity, only one chiller needs to run for a fraction of the determined charging period. In that case, the actual tank charging period will be less than what is already determined, since the chillers are almost always fully loaded during the charging cycle. The actual charging hours is:

$$H_{chg} = \frac{L_p}{C_{chlr}}$$

The chiller start/stop sequence is determined as:

- The lead chiller starts at T_{cs}, and stops at the $T_{cs}+H_{chg}$;
- Neither the lag chiller or the backup chiller will be started.

If Rp is between the capacity of a single chiller and two chillers, the lead chiller will be turned on for the entire charging period and the lag chiller will run for a fraction of the charging period. The runtime for the lag chiller is calculated as

$$H_{lag} = H_{tot} - H_{chg}$$

Obviously, the lead chiller starts at T_{cs} and stops at T_{ds}. In determining the lag chiller's start-stop times, it is attempting to start the lag chiller at T_{cs}, and let it run for H_{lag} hours. However, this may bring forth certain unexpected result in the tank charging process.

Theoretically, the best charging process would be fully load the lead chiller and partially load the lag chiller for the entire period of the charging process. That way, there is no chiller start/stops within the charging period and the tank is charged smoothly from empty to full. However, due to the complicated control involved in regulating chiller load, and more importantly due to potential chiller efficiency degradation under low load conditions, the chillers are simply fully loaded during the charging period once they are running. This means that the lag chiller only needs to run for part of the entire charging process. Assuming the tank charging cycle is determined to start at 22:00 and stop at 14:00 the next afternoon, which is a 16-hour charging period. Also assume the total chiller hours needed is 29 hours. Therefore, the lead chiller runs through all the charging period, while the lag chiller runs from 22:00 through 11:00 the next morning, fully loaded. Mathematically, this charging scenario would charge the tank to the same level (i.e., a full tank) as the theoretical load-regulating process described earlier. However, for this particular scenario, since only one chiller is running from 11:00 to 14:00, the tank may very likely "discharging" during this period. This means the tank would have to be "overcharged" at 11:00 in order to still have a full tank at 14:00, which is impossible. The imaginary charging process for this scenario is shown as "Unwanted process" in Figure 7. Due to the limit of the tank capacity, the actual process under this scenario is shown in Figure 7 as "Unwanted Process II". The tank actually starts to discharge from 11 a.m., and it will be depleted around 8 p.m. In consequence, this forces the next charging process to be started as early as 8 p.m., instead of 10 p.m. This is obviously undesired scenario.

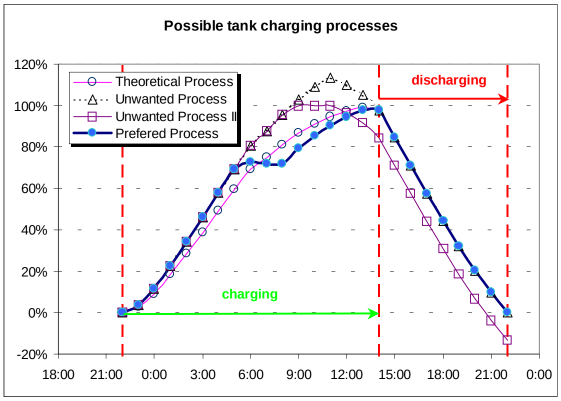

Figure 7. Comparison of possible charging processes

The lag chiller could also be brought on at a later time (in this case, 3 hours later than the lead chiller) and keep it running all the way to 2 p.m. This tank will be fully charged as expected. However, this means the lag chiller would be turned on around 1 a.m. This is unacceptable to the physical plant for the reason has been explained earlier. Therefore, the only choice left is to break the lag chiller's runtime into two parts, both starts at a time when someone can watch the chiller starting. One of the many possible schedules is to start the lag chiller at the same time as the lead chiller and shut it down sometime overnight at Tx (to be determined later). The lag chiller (or the backup chiller) is then started again at 8 a.m., and kept running until the end of the charging period. Of course, if the lag chiller only needs to run for a few hours, its runtime may not need to be broken into two periods. The lag chiller can simply be started the a few hours earlier before the end of the charging cycle, as long as it doesn't have to be started earlier than 8 a.m.

In summary, the chiller start-stop sequence is determined as:

- The lead chiller will be started at T_{cs}, and shut down at T_{ds};
- The lag chiller will be shut down at the same time as the lead chiller (T_{ds}).
- If the lag chiller's runtime (H_{lag}) is less than one hour shorter than that of the lead chiller (H_{led}), the difference can be disregarded, and the lag chiller will be started at the same time as the lead chiller
- Otherwise, if H_{lag} is more than one hour shorter than H_{led}, the two chillers will have different runtimes. The ideal time to start the lag chiller would be

  $$T_{ideal} = T_{ds} - H_{lag}$$

  If T_{ideal} is later than 8 a.m., this will be the time to start the lag chiller; otherwise, the lag chiller runtime has to be broken into two parts. The second part is from 8 a.m. to T_{ds}. The first part is from T_{cs} to T_x, where

  $$T_x = H_{lag} - (T_{ds} - 8)$$

- The backup chiller will not be started.

The flow chart of the chillers start-stop optimization program is attached at the end of this paper (see Figure 10).

SAMPLE CASE

The scheduling process may be better illustrated by a real numbered example. On 10 p.m. of July 4, 2002, the thermal storage tank has around 950 ton-hour equivalent of chilled water left. From weather channel, the overnight low for July 4 (Thursday) and daytime high for July 5 (Friday) are 80 and 90 °F respectively. For certain reason, the chillers are not able to deliver their designed capacity. Instead of supplying the designed 42 °F chilled water, these chillers are only able to supply 43 °F chilled water, with the designed return temperature (56 °F) and chilled water flow (1,720 gpm). Consequently, the chiller's full load capacity is around 932 ton, and the thermal storage tank's capacity is also reduced to around 118,401 ton-hour. Based on these conditions, the chiller start-stop sequence is to be determined for the next 24 hours.

From the outside air temperature prediction model and the load model developed, the hour-by-hour ambient temperatures and corresponding campus cooling loads can be predicted for the next 24 hours, as shown in Table 2. Certain load factors have been developed to take into account for the reduced load during the summer school session and the reduced load for night setback (12 a.m. to 6 a.m.).

Table 2. Hour-by-hour prediction for OAT and campus load

Data/Time	Electricity Rate	Predicted OAT (deg F)	Predicted Load (ton)	Load factor	Final predicted Load (ton)
7/4/02 22:00	2	83.7	1,306	0.92	1,202
7/4/02 23:00	2	82.5	1,251	0.92	1,151
7/5/02 0:00	1	81.5	1,204	0.63	759
7/5/02 1:00	1	80.7	1,168	0.63	736
7/5/02 2:00	1	80.2	1,145	0.63	722
7/5/02 3:00	1	80.0	1,138	0.63	717
7/5/02 4:00	1	80.2	1,145	0.63	722
7/5/02 5:00	1	80.7	1,168	0.63	736
7/5/02 6:00	1	81.5	1,204	0.92	1,108
7/5/02 7:00	1	82.5	1,251	0.92	1,151
7/5/02 8:00	2	83.7	1,306	0.92	1,202
7/5/02 9:00	2	85.0	1,365	0.92	1,256
7/5/02 10:00	3	86.3	1,424	0.92	1,310
7/5/02 11:00	3	87.5	1,479	0.92	1,360
7/5/02 12:00	3	88.5	1,526	0.92	1,404
7/5/02 13:00	3	89.3	1,562	0.92	1,437
7/5/02 14:00	4	89.8	1,585	0.92	1,458
7/5/02 15:00	4	90.0	1,593	0.92	1,465
7/5/02 16:00	4	89.8	1,585	0.92	1,458
7/5/02 17:00	4	89.3	1,562	0.92	1,437
7/5/02 18:00	4	88.5	1,526	0.92	1,404
7/5/02 19:00	4	87.5	1,479	0.92	1,360
7/5/02 20:00	3	86.3	1,424	0.92	1,310
7/5/02 21:00	3	85.0	1,365	0.92	1,256

The total campus cooling load (L_c) for the next 24 hours was estimated at 28,119 ton-hr. The actual total chiller load of the next charging cycle is determined as

$L_p = L_c - L_e + L_b$, where L_e is the tank left capacity, and L_b is a fixed backup load, which is 500 ton-hr in this case. The total chiller load is therefore calculated to be 27,669 ton-hr.

To determine the tank discharging period, hourly loads were added up starting from the most expensive hours to less expensive hours in this order: 14:00, 15:00, 16:00, 17:00, 18:00, 19:00, 20:00, 21:00, 13:00, 12:00, 11:00, 10:00… until the total amount reaches the tank capacity. It was determined that the tank (if fully charged) can provide the chilled water needs to the campus from 13:25 to 22:00 on July 5. Automatically, the tank charging period starts from 22:00 on July 4 (T_{cs}), and stops at 13:25 on July 5 (T_{ds}). The tank charging period (H_{chg}) lasts for around 15.5 hours.

The average chiller production rate

$$R_p = \frac{L_p}{H_{chg}} = \frac{27{,}669}{15.5} = 1{,}785\ (ton)$$

The total required chiller hours

$$H_{tot} = \frac{L_p}{C_{chlr}} = \frac{27{,}669}{932} = 29.68\ (hour)$$

Since R_p is between the capacity of one chiller and two chillers, two chillers will be involved in the charging process. The lead chiller run through the entire charging process, i.e., it starts at 22:00 on July 4 and stops at 13:25 on July 5. The runtime for the lag chiller

$$\begin{aligned} H_{lag} &= H_{tot} - T_{chg} \\ &= 29.68 - 15.5 = 14.18 \quad (hour) \end{aligned}$$

The lag chiller's runtime is about 1.3 hours less than the lead chiller's runtime. Depending on the actual operating practice, the lag chiller can simply be kept on through the entire charging period, just like the lead chiller. More precise control is to run the lag chiller for 14.18 hours only.

If the second option is selected, the lag chiller's runtime should be broken into two separated parts as described in the previous section, which can be called the overnight run period and the morning run period. The morning run period starts from 8:00 to the end of the charging process, i.e. 13:25, a period of approximately 5.4 hours. This leaves the overnight period for approximately 8.78 hours. The lag chiller's overnight run period starts from 22:00 on July 4, and stops at around 6:46 on July 5.

According to typical chiller operating practice, a certain period of time should be allocated between successive chiller start-stops. In this case, a 15 minutes time interval has been set. Taking this into account, the final chillers start-stop sequence is determined as following:

- The lead chiller starts at 22:06 on July 4 and stops at 13:25 on July 5.
- The lag chiller starts at 22:22 on July 4 and stops at 6:50 on July 5.
- The backup chiller starts at 8:00 on July 5 and stops at 13:41 on July 5.

The backup chiller was started instead of the lag chiller at 8:00 to avoid frequent chiller start stops.

With all the chillers start and stop times determined, the total chiller production at each hour will be known. Since the campus load has already been predicted for each hour as well, the amount of chilled water being charged to or taken out from the thermal storage tank can therefore be predicted hour by hour for the next 24 hours. Also, the chilled water levels at each hour can also be estimated. The hourly campus load, chiller production and tank charging (and discharging) rates are calculated and shown in Table 3 and Figure 8.

The chillers start stop program implemented in the control system carried out the calculation in the exactly same way, and the determined chiller start-stop sequence was executed accordingly. With the 30 temperature sensors installed on the thermal storage tank, the changes in the tank's chilled water level can be monitored. The measured and the predicted tank level changes at each hour for the next 24 hours are show in Figure 9. The simulated process matches the actual process closely, especially for the discharging process. The charging process between midnight to 6 a.m. seems to be a little faster than the predicted process, which suggests for this particular period, the campus load was slightly overestimated.

The variation in the campus load from day to day can be caused by many factors other than the outside air temperature, such as the humidity level of the outside air, building operation schedule, special events, etc. However, if a systematic offset is observed consistently between the simulated and the measured processes, it may suggest a permanent change in campus load has been introduced and the load prediction models need to be adjusted accordingly by changing the load factors for certain period of time.

Table 3. Predicted tank charging/discharging process

Date/Time	Predicted Campus Load (ton)	Total Chiller Load (ton)	Accu.Tank Load (ton-hr)	Tank Level (feet)	Tank Level (%)
7/4/02 22:00	1,202	1,429	281	4.8	8%
7/4/02 23:00	1,151	1,863	1,178	6.0	10%
7/5/02 0:00	759	1,863	1,890	9.6	16%
7/5/02 1:00	736	1,863	2,995	15.2	25%
7/5/02 2:00	722	1,863	4,122	20.9	35%
7/5/02 3:00	717	1,863	5,264	26.7	44%
7/5/02 4:00	722	1,863	6,411	32.5	54%
7/5/02 5:00	736	1,863	7,553	38.3	64%
7/5/02 6:00	1,108	1,475	8,680	44.0	73%
7/5/02 7:00	1,151	932	9,047	45.8	76%
7/5/02 8:00	1,202	1,863	8,828	44.7	75%
7/5/02 9:00	1,256	1,863	9,490	48.1	80%
7/5/02 10:00	1,310	1,863	10,097	51.2	85%
7/5/02 11:00	1,360	1,863	10,651	54.0	90%
7/5/02 12:00	1,404	1,863	11,153	56.5	94%
7/5/02 13:00	1,437	1,025	11,613	58.8	98%
7/5/02 14:00	1,458	-	11,201	56.8	95%
7/5/02 15:00	1,465	-	9,743	49.4	82%
7/5/02 16:00	1,458	-	8,278	41.9	70%
7/5/02 17:00	1,437	-	6,820	34.6	58%
7/5/02 18:00	1,404	-	5,383	27.3	45%
7/5/02 19:00	1,360	-	3,979	20.2	34%
7/5/02 20:00	1,310	-	2,618	13.3	22%
7/5/02 21:00	1,256	-	1,308	6.6	11%
			53	0.0	0%

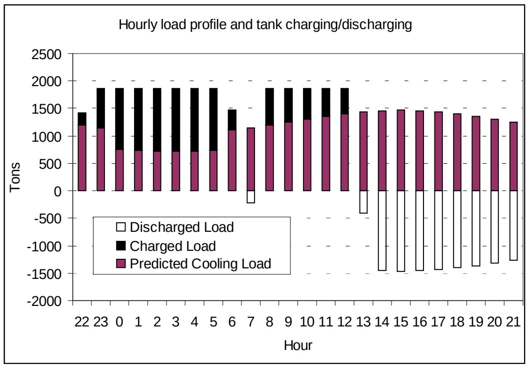

Figure 8. Hourly load profile and tank charging (discharging) process

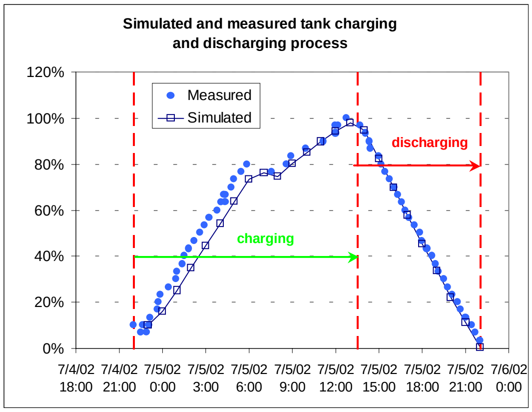

Figure 9. Simulated and measured tank level at different hours

CONCLUSIONS

The chiller start stop optimization program developed specially for the four-period electricity rate structure saves operational costs by operating the chillers in the lower-price time periods. The concept is easy to grasp when the rate schedule is relatively simple. However, when the rate schedule is getting more complicated, more sophisticated analysis is required for every individual scenario. Chiller starts-stops based solely on operators' experience and general judgment may not be enough to make the best decision. The computer program automated the decision-making process for daily chillers scheduling. This makes sure the chillers are always operated under a near-optimum scenario for different load conditions. Of course, the program can never optimize the system's operation for every single day, simply because the model can not predict the campus's real load with 100% accuracy 24 hours ahead. However, the program does have the flexibility to be easily adjusted to reflect the changes in campus's load pattern.

REFERENCES

1. ASHRAE. 1999. *ASHRAE Handbook-HVAC Applications*. Atlanta, GA.

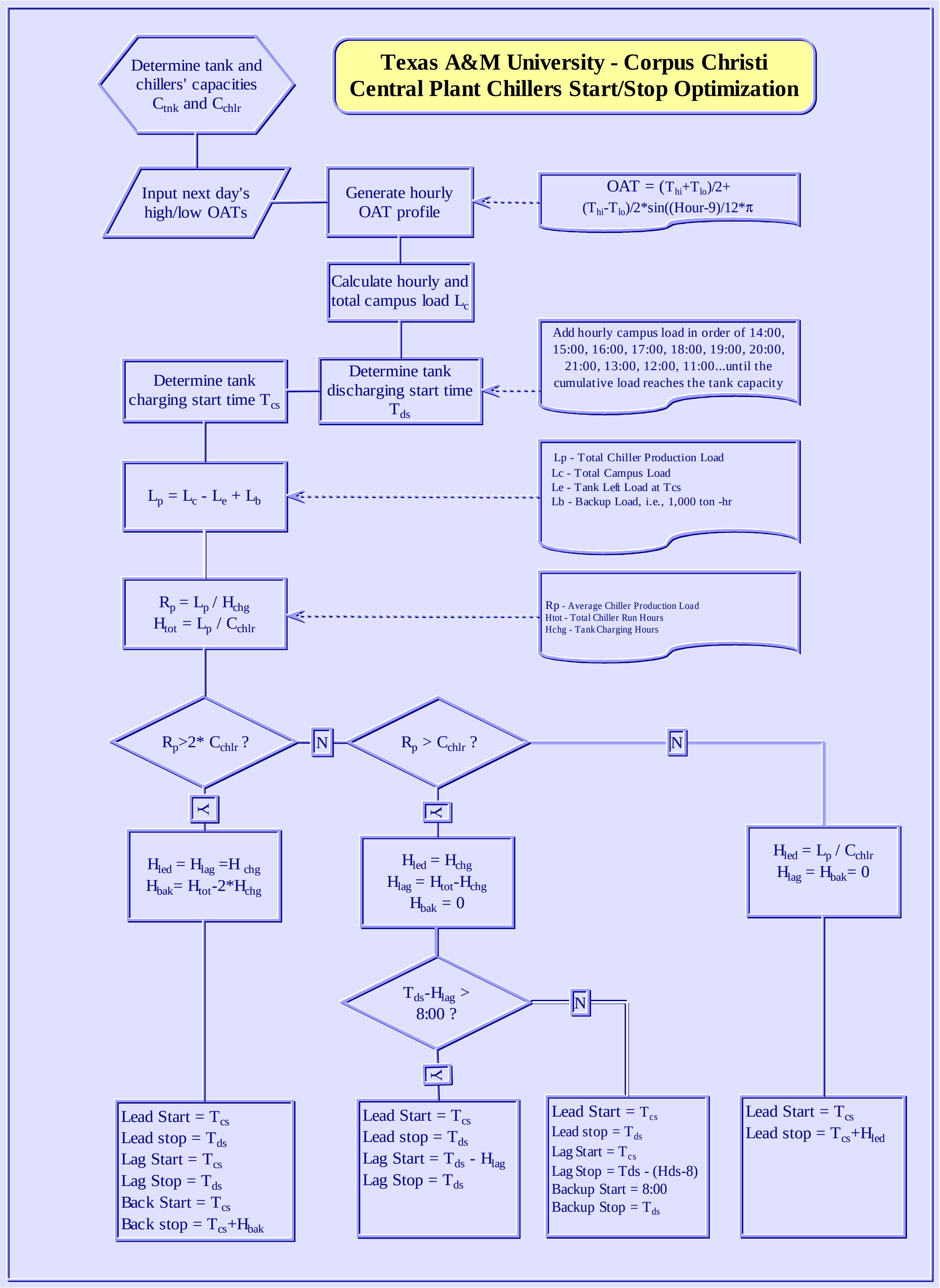

Figure 10. Chillers start/stop optimization program flow chart