CALIBRATION OF AN ENERGYPLUS CENTRAL COOLING PLANT MODEL WITH MEASUREMENTS AND INTER-PROGRAM COMPARISON

Danielle Monfet[1] and Radu Zmeureanu[2]
[1]Department of Construction Engineering, École de technologie supérieure, Montréal, Canada
[2]Centre for Net-Zero Energy Building Studies, Department of Building, Civil and Environmental Engineering, Faculty of Engineering and Computer Science, Concordia University, Montréal, Canada

ABSTRACT

This paper, which is an extension of previous studies, presents the modeling of an existing central cooling plant by using the EnergyPlus program. The previously identified coefficients of the chiller model and additional performance values/curves obtained using measured data are used to develop and calibrate the model. Differences in performance values and curves required by both the EnergyPlus and TRNSYS programs are presented as well as issues related to modeling the central cooling plant in those programs.

The EnergyPlus simulation results are compared with measured data and then with the TRNSYS simulation results for a few days in the summer. The results show that it is possible to develop a calibrated model using measurements without modifying by trial-and-error some variables or using stochastic approaches.

INTRODUCTION

The development and use of calibrated building simulation models to assess energy performance, identify operation issues, propose retrofits, and evaluate new control strategies is rapidly gaining acceptance. Different calibration approaches are used by consultants and researchers depending, for example, on the availability of measured data, time and resources allocated to the calibration, and the user's experience with both the software tool and HVAC systems. In most cases, the use of default performance values of HVAC equipment, which are available in the detailed energy analysis programs, are used in the model. This can lead to inacurate energy use prediction at the equipment level and consequently it might be difficult to use the calibrated model for other purposes than evaluating the whole building energy performance. Thus, more attention should be given to the use of measurement of relevant parameters and the identification of performance values/curves for major HVAC equipment for model calibration.

The identification of the coefficients of the chiller model used by the EnergyPlus program was previously proposed using data collected every 15 minutes from an existing cooling plant (Monfet and Zmeureanu 2011). The identified coefficients for the performance curves generated an accurate prediction of the electric power input to chillers over the summer season 2009.

The identification of model parameters or coefficients of performance curves using monitored data collected via the Monitoring and Data Acquisition System (MDAS) provided the basis for the calibration of a TRNSYS model of the existing cooling plant. This model included chillers, cooling towers, heat recovery heat exchanger and pumps (Monfet and Zmeureanu 2013). The proposed calibration approach was based on (1) the identification of unknown parameters and performance curves of major equipment with data extracted from a sub-set of measurements over the summer 2009 and from manufacturer's catalogues data; (2) the replacement of new identified values in the input files; and (3) the comparison between the predictions and measurements.

In this paper, the same existing central cooling plant is modeled in EnergyPlus. The previously identified coefficients of the chiller model and additional performance values/curves obtained using measured data are used to develop and calibrate the model.

The EnergyPlus simulation results are compared with measured data and then with the TRNSYS simulation results for a few days in the summer. Differences in performance values and curves required by both simulation software tools are presented, as well as issues related to modeling the central cooling plant in EnergyPlus and TRNSYS. Finally, recommendations are presented to improve the use of monitored data to identify the performance of major equipment for calibration of building simulation models.

BACKGROUND INFORMATION

Several studies have demonstrated the use of calibrated simulation models to identify opportunities to improve the whole building energy performance (e.g. Lawrence and Braun. 2007, Lee et al. 2007, and Pan et al. 2007). Different procedures have been proposed to calibrate computer models (e.g. Pedrini et al. 2002, Yoon et al. 2003, Sun and Reddy 2006, Reddy et al. 2007a,b and Lui and Lui 2011).

Two different statistical criteria have been used to evaluate if the developed model is calibrated: the coefficent of variance of the root-mean-square error (CV-RMSE) defined by Equation (1), and the normalized mean bias error (NMBE) defined by Equation (2). According to ASHRAE Guideline 14 (ASHRAE 2002), the model of whole building performance is calibrated on the hourly basis if the NMBE is within 10% of hourly measurements and CV-RMSE within 30%. Kaplan et al. (1990) proposed different levels of tolerances in terms of the type of end-use and the interval of time used for comparison. In the case of HVAC systems, the proposed tolerances are 25□35% for daily values. No indications are given for hourly or sub-hourly data.

$$CV - RMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{n-1}}}{\bar{y}} \times 100 \quad (1)$$

$$NMBE = \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)}{(n-1)\times\bar{y}} \times 100 \quad (2)$$

where y_i is the measured value, $\hat{y}_i$ is the predicted value, $\bar{y}$ is the mean of the measured value sample data, and n is the number of data.

DESCRIPTION OF THE CENTRAL COOLING PLANT

Information about the as-built and as-operated thermal performance of the central cooling plant is obtained through the collaboration of the Physical Plant of Concordia University from the Monitoring and Data Acquisition System (MDAS). The system uses a leading controls manufacturer's DDC control system. Data monitored every 15 minutes for the summer 2009, from June 22 to September 20, are selected to analyze and identify the operating characteristics of the cooling plant. The accuracy of selected measurements is presented in Table 1 and uncertainties are estimated by using information presented in ASHRAE Guideline 2-2005 (ASHRAE 2005).

Table 1
Accuracy information for selected measurements

ITEM	ACCURACY	ZERO-DRIFT
Water flow meter	1%	0.5%
Chiller power	5%	□
Temperature	±1°C	□

The cooling plant has two centrifugal chillers, CH1 and CH2, which provide chilled water to the air handling units installed in two buildings. The chillers use R-123 refrigerant, have a cooling capacity of 3165 kW (900 tons) each, and the rated power input is 549 kW with a coefficient of performance (COP) of 5.76 at design conditions. The average measured supply (leaving) chilled water temperature is 6.7°C (T_{CHWS}) and the return is 11.25°C (T_{CHWR}). When the first chiller is started, the corresponding chilled water and condenser water pumps are started simultaneously. The fans of the cooling towers are started when the condenser pumps are started, if required. The second chiller is started only if the chilled water demand is not met by the first chiller. In this case, the second set of pumps and cooling tower is also started.

The chillers are water-cooled by two perpendicular flow cooling towers, CT1 and CT2, having a capacity of 4750 kW (1350 tons) each at design conditions. The average measured condenser water temperature entering the cooling tower is 33.3°C (T_{CNDS}) and leaves at 29.0°C (T_{CNDR}). During the summer, one of the chillers can operate under heat recovery mode. For that chiller, 55% of the water flow rate (pump P5) from the condenser is directed first to a heat exchanger (HX3) to pre-warm the heating water return, and then mixed with the remaining 45% before being sent to the cooling tower. A simplified schematic of the central cooling plant configuration is presented in Figure 1. Also, based on measurements, during the summer of 2009, the chillers account for 65% of the total electricity use for cooling, cooling towers 2% and all pumps of the chilled water side 33%.

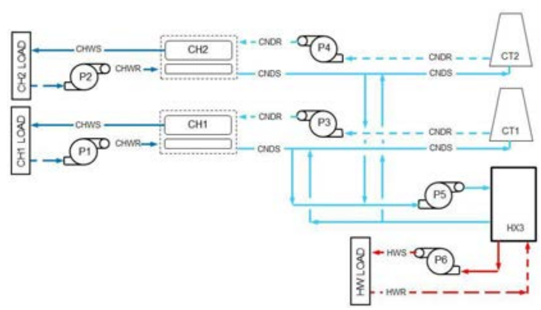

Figure 1 Central cooling plant schematic

DEVELOPMENT OF THE ENERGYPLUS MODEL

EnergyPlus simulation requires both a weather file in EPW format and an input file. To improve the simulation results, the EPW file used for Canadian Weather for Energy Calculations (CWEC) is replaced by the EPW file available from the Hydro-Québec□s Laboratoire des Technologies de l□Énergie (LTE) website for the year 2009 (https://www.simeb.ca:8443/index_fr.jsp). This file corresponds to hourly measurements of weather variables at the Dorval airport for the entire year.

The EnergyPlus input file is developed by combining example files and default equipment information provided within these files. Four example files were used to develop the model: Plant Load Profile, Electric EIR Chiller, Plate Heat Exchanger, and Cooling Tower Variable Speed MultiCell.

The cooling equipment is divided into three groups: (1) chiller CH1 and cooling tower CT1, (2) chiller CH2 and cooling tower CT2, and (3) heat exchanger HX3. From 22 June to 16 July 2009, the chiller CH2 and cooling tower CT2 are the first group of equipment to be start-up, while after 6 July 2009, the chiller CH1 and the cooling tower CT1 become the first group of equipment to be started-up, when required.

At this stage, separate heat recovery loops are created for the first two equipment groups. The heat exchanger HX3 and pumps P5 and P6 are duplicated but only operate according to the specified schedule, i.e. pumps P5, P6 and heat exchanger HX3 connected to the CH1-CT1 loops never operate at the same time as pumps P5, P6 and heat exchanger HX3 connected to the CH2-CT2 loops. This simplification ensures the operation of the system is controlled properly.

The flow chart of the model developed in EnergyPlus is presented in Figure 2 for the CH1-CT1 equipment group. The configuration for the CH2-CT2 equiment group is identical. The interaction between the heating water loop and the condenser water loop is modeled using the heat exchanger. The inputs to the model used to simulate the major equipment are presented in the following sections.

Load Profiles

The chilled water and heating water loads are simulated using the scheduled demand profile using the LoadProfile:Plant object. This object requires the demanded load and flow rate to be specified in schedules (DOE 2012). The schedules are input using the Schedule:File object, which reads in hourly schedules computed by other software or developed in a spreadsheet or other utility. This object is limited to hourly input and must contain values for an entire year (8760 lines of data) and the first row of data must be for January 1, hour 1 (DOE 2012). Since data monitored on-site are recorded every fifteen minutes; the hourly average values are calculated and used in the input to Schedule:File object.

Chillers

The two chillers are modeled using the EnergyPlus ReformElectricEIRChiller model. The selected EnergyPlus model simulates the electric power input (P_E) in kW of an electric liquid chiller based on the chilled water supply temperature (T_{CHWS}), the temperature leaving the condenser (T_{CNDS}), both in °C, and the evaporator load (Q_E) in kW. The chiller power input (P_E), in kW, is determined using Equation (3).

$$P_E = Q_{avail} \times (1/COP_{ref}) \times EIRFTemp \times EIRPFPLR \qquad (3)$$

where, Q_{avail} is the available cooling capacity of the chiller in kW, defined by Equation (4);

$$Q_{avail} = Q_{ref} \times CapFTemp \qquad (4)$$

where Q_{ref} and COP_{ref} are the chiller capacity and coefficient of performance respectively, at reference conditions (reference temperatures and flow rates defined by the user); *CapFTemp* is the cooling capacity factor for different operating temperatures, *EIRFTemp* is the energy input to cooling output ratio at full load, *EIRFPLR* is the energy input to cooling output ratio at part load ratio.

A list of different chillers is available in EnergyPlus. The chillers installed in the central cooling plant are Trane CVHF0910 model with COP of 5.76 at design conditions. This model is not available as a default in EnergyPlus. Therefore, the Trane chiller model that has the closest capacity, which is the Trane CVHF0796 with COP_{ref} of 6.4, is initially used in this study.

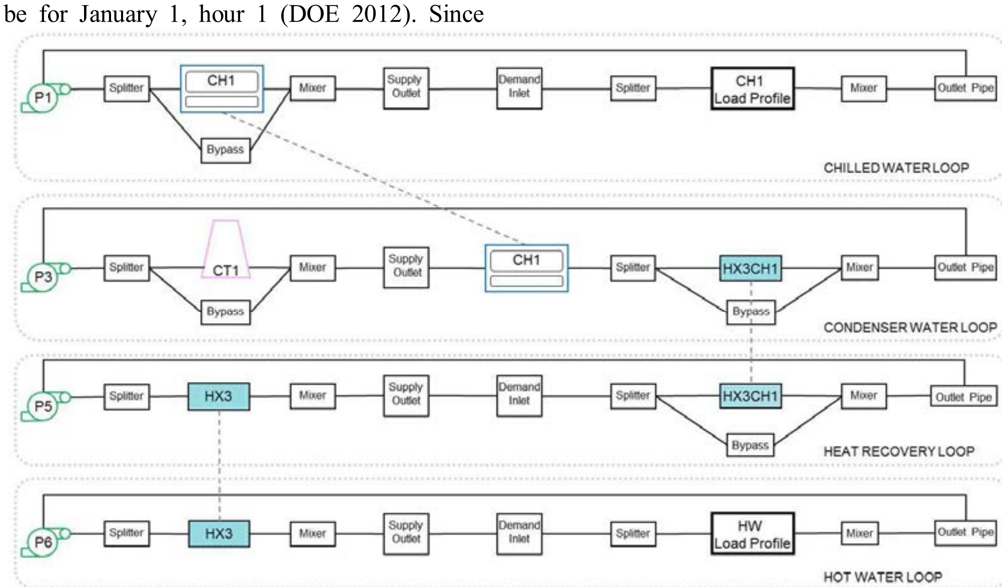

Figure 2 EnergyPlus flow chart for CH1-CT1 equipment group

The coefficients of the performance curves *CapFTemp*, *EIRFTemp*, and *EIRFPLR* can also be generated using manufacturer's data or measured data. The Hydeman and Gillespie (2002) technique, which is based on Hydeman et al. (2002), was used with some modifications for the identification of the coefficients a_j, b_j, and c_j for the chiller installed in the central cooling plant (Monfet and Zmeureanu 2011). 28-days of data for the first chiller and 7-days of data for the second chiller, collected at the beginning of the summer season 2009, were sufficient to obtain accurate prediction of the electric power input to chillers: the CV-RMSE for the electric power input was between 3.7% and 7.4% for both chillers. The identified coefficients using the CH1-28D and CH2-7D data sets are used in the simulation and presented in Table 2.

Table 2
Coefficients for the electric power input models for chillers (Monfet and Zmeureanu 2011)

ITEM	PROGRAM DEFAULT FOR CHILLER	IDENTIFIED FROM MEASUREMENTS	
		CHILLER CH1-28D	CHILLER CH2-7D
Q_{ref}	2799 kW	2666 kW	2928 kW
P_{ref}		517 kW	527 kW
COP_{ref}	6.4	5.157	5.556
a_0	-0.21763	55.68490	11.99170
a_1	-0.04941	-5.92140	-7.77910
a_2	0.00009	0.13986	0.71449
a_3	0.09612	-1.98856	0.86498
a_4	-0.00203	0.01810	-0.00760
a_5	0.00253	0.11092	-0.05142
b_0	-0.01987	-42.71440	-51.58040
b_1	-0.07848	6.25958	22.43780
b_2	0.00194	-0.19697	-2.30418
b_3	0.07123	1.19876	-1.34114
b_4	-0.00092	-0.00736	-0.00378
b_5	0.00058	-0.09546	0.24441
c_0	0.35162	1.94517	2.33977
c_1	0.00921	-0.01389	-0.08433
c_2	-0.00002	-0.00150	0.00065
c_3	0.12232	-1.91033	-1.91995
c_4	-0.18201	-1.53332	-0.10428
c_5	-0.00784	0.12419	0.07856
c_6	0.68848	0.46424	0.03295

Cooling towers

The CoolingTower:VariableSpeed object is used in the simulation. Empirical curves are used to determine the approach temperature (T_a) in °C and fan power in W at off-design conditions using manufacturer's performance data or field measurements (DOE 2012). The initial simulation is performed using the default empirical curves for the approach temperature and fan power at off-design conditions, with only the design water flow rate of 0.1315 m^3/s and fan power of 6000 W specified in the input file. The YorkCalc correlation default curve is selected to model the approach temperature (T_a). The YorkCalc correlation uses three independent variables - inlet air wet-bulb temperature (T_{wb}) in °C, tower range temperature (T_r) in °C, and the liquid-to-gas ratio (LG), dimensionless - and 27 coefficients (d_i) to model the approach temperature; where T_a is defined by Equation (5), T_r by Equation (6), and LG by Equation (7).

$$T_a = T_{CT,out} - T_{wb} \tag{5}$$

$$T_r = T_{CT,in} - T_{CT,out} \tag{6}$$

$$LG = m_w / m_{w,d} \div m_a / m_{a,d} \tag{7}$$

where $T_{CT,out}$ is the cooling tower outlet water temperature in °C; T_{wb} is the inlet air wet-bulb temperatue in °C; $T_{CT,in}$ is the cooling tower inlet water temperature in °C; m_w and $m_{w,d}$ are the cooling tower actual and design water flow rates respectively, in m^3/s; m_a and $m_{a,d}$ are the coolling tower actual and design airflow rate respectively, in m^3/s.

To improve the simulation results, the curves for fan power at off-design conditions are modified using measured data. This cubic curve uses the air flow rate ratio to estimate the fan power ratio (Equation (8)). Since the cooling towers are operating when their respective chillers are in operation, a data set of 28-days of data for CT1 and 7-days of data for CT2, collected at the beginning of the summer season 2009, are used to identify the model coefficients. Table 3 presents the default curve coefficients as well as the identified coefficients.

$$\frac{P_F}{P_{F,r}} = a + b\frac{m_a}{m_{a,d}} + c\left(\frac{m_a}{m_{a,d}}\right)^2 + d\left(\frac{m_a}{m_{a,d}}\right)^3 \tag{8}$$

where, P_F and $P_{F,r}$ are the actual and rated cooling tower fan power respectively in W; m_{air} and $m_{a,d}$ are the actual and design cooling tower fan airflow rate respectively, in m^3/s.

Table 3
Coefficients for the fan power input model at off-design conditions for cooling towers

	PROGRAM DEFAULT FOR CHILLER	IDENTIFIED FROM MEASUREMENTS	
		CT1-28D	CT2-7D
a	-0.00932	-4.27214E-9	-2.11451E-9
b	0.05123	2.49146E-8	1.10763E-8
c	-0.08384	-4.68281E-8	-1.87182E-8
d	1.04192	0.994267	0.994267

Heat exchanger

In the proposed loop configuration, the HeatExchanger:Plate object is used to model the interaction between the condenser, heat recovery and heating water loops. The heat exchanger heat transfer rate was evaluated at 463 kW/K based on measured data (Monfet and Zmeureanu 2013).

Pumps

The EnergyPlus inputs to the Pump:ConstantSpeed component, which are based on measurements and technical specifications, are presented in Table 4.

Table 4
Input pump information

PUMPS	TAG	FLOW, m^3/s	HEAD, kPa	POWER, kW
Evaporator (CHW)	P1 P2	0.087	657	75
Condenser (COND)	P3 P4	0.110	209	56
HX, condenser side (COND)	P5	0.060	194	30
HX, heating water side (HW)	P6	0.10725	179	30

SIMULATION RESULTS AND COMPARISON WITH MEASURED DATA

The predictions of the EnergyPlus model with the identified input data are compared with measured data and predictions of the TRNSYS model (Monfet and Zmeureanu 2013) over (a) the week of 27 July to 2 August 2009, and (b) over the entire summer, 22 June to 20 September 2009.

Calibrated predictions versus measurements: 27 July to 2 August 2009

The measurements uncertainty ranges for the electric power input ($P_{E,CH1}$) and COP_{CH1} are shown in Figures 3 and 4 rather than the actual measurements. The predictions made by EnergyPlus compare well with measured data for chiller CH1. The electric power input ($P_{E,CH1}$) is slightly overestimated by EnergyPlus, while the (COP_{CH1}) is within the measured uncertainty range.

For the cooling tower CT1, the estimated electricity power input ($P_{E,CT1}$) follows the same trend as the measured value; however, the values are overestimated (Figure 5). The EnergyPlus cooling tower model is greatly influenced by the air wet-bulb temperature and input design criteria. The outdoor wet-bulb temperature estimated for the actual site conditions using the measured dry-bulb temperature and outdoor air relative humidity is on average 2.6°C lower over the summer 2009 than the wet-bulb temperature recorded at the airport, and used in the weather data file. For the week of 27 July to 2 August, the EnergyPlus outdoor wet-bulb temperature is up to 5.5 °C higher than the value measured on-site and used in the TRNSYS simulation . Futhermore, no changes have been made to the default YorkCalc approach temperature curve, which is defined as a function of air wet-bulb temperature, tower range temperature, and the liquid-to-gas ratio.

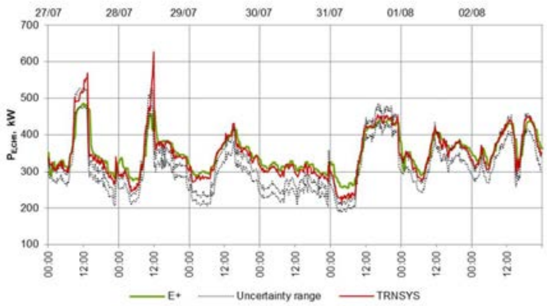

Figure 3 Predicted versus measured electric power input for CH1, 27 July to 2 August 2009

Figure 4 Predicted versus measured COP for CH1, 27 July to 2 August 2009

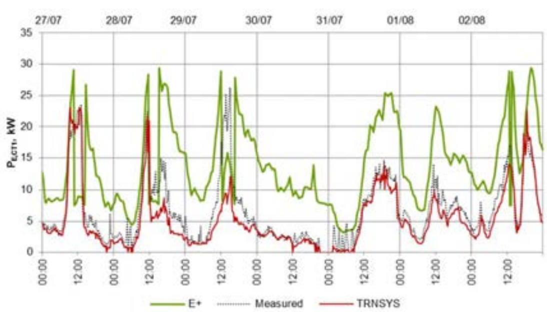

Figure 5 Predicted versus measured electric input for CT1, 27 July to 2 August 2009

Calibrated predictions versus measurements over the entire summer: 22 June to 20 September 2009

Results are presented for (i) the calibrated EnergyPlus model, (ii) the EnergyPlus model developed using default performance curves and (iii) the calibrated TRNSYS model. In terms of water temperature at key locations, the predictions made by the EnergyPlus calibrated model compared with measurements are within the uncertainty level of temperature measurements (Table 5).

Table 5
Predicted versus measured water temperatures at key locations for CH1-CT1, 22 June to 20 September 2009

ITEM	**ENERGYPLUS**		**TRNSYS**	
	MBE, °C	RMSE, °C	MBE, °C	RMSE, °C
T_{CHWS}	-0.1	0.4	-0.1	0.3
T_{CNDS}	-0.2	0.8	1.6	1.4
$T_{CNDR}/T_{CT,out}$	0.1	0.4	1.4	1.6

The CV-RMSE and NMBE are calculated for the electric power input to the chiller over the entire summer 2009 with a 15-min time-step (Table 6). For chiller CH1, the CV-RMSE is slighlty higher in EnergyPlus, while being lower for CH2 compared to predictions made by TRNSYS. For both models, the simulation results are well within the recommended values by ASHRAE (2002) of 30% and 10% for hourly measurements for the CV-RMSE and NMBE, respectively.

Table 6
Predicted versus measured electric power input to chillers, in %, 22 June to 20 September 2009

	E+ CALIBRATED		**E+ DEFAULT**		**TRNSYS**	
	CV	NMBE	CV	NMBE	CV	NMBE
CH1	15.3	5.9	16.1	3.2	11.4	-6.6
CH2	15.1	-4.1	17.1	2.3	19.1	-15.6

The electricity use over the summer is presented in Table 7, where CH refers to chillers, CT to cooling towers, and P to pumps, while Table 8 presents the seasonal relative errors (R.E.), defined by Equation (9). The calibrated EnergyPlus model slightly overestimates the energy use over the summer.

$$R.E. = \frac{\sum(\hat{y}_i \times \Delta t) - \sum(y_i \times \Delta t)}{\sum(y_i \times \Delta t)} \tag{9}$$

where y_i is the measured value, $\hat{y}_i$ is the predicted value, and t is the time interval, in this case 15 minutes.

Table 7
Predicted versus measured cooling electricity use, in kWh, 22 June to 20 September 2009

ITEM	**CH**	**CT**	**P1 to P5**	**TOTAL**
Measured	604 424	14 886	309 372	928 682
E+ Calibrated	649 546	20 208	358 919	1 028 673
E+ Default	588 997	23 438	358 919	971 353
TRNSYS	662 089	13 587	303 746	979 423

Table 8
Seasonal R.E., in percentage, 22 June to 20 September 2009

ITEM	**CH**	**CT**	**P1 to P5**	**TOTAL**
E+ Calibrated	7.5	35.8	16.0	10.8
TRNSYS	9.5	-8.7	-1.8	5.5

COMPARISON BETWEEN ENERGYPLUS/TRNSYS AND DISCUSSION

The approach undertaken to simulate and calibrate the central cooling plant in EnergyPlus and TRNSYS is quite similar: (1) input the scheduled chilled water and heating water load profiles; (2) identify unknown parameters and performance curves of major equipment with data extracted from a sub-set of measurements over the summer 2009 and from manufacturer's catalogues data; (3) replace the new identified values in the input files; and (4) compare the predictions with measurements. Both programs provide predictions in good agreement with measurements. Differences and issues between the two software tools are highlighted in the following sections.

Development of the model

The development of simulation models in EnergyPlus and TRNSYS are quite different. For the EnergyPlus program, various interfaces are under development; however, they often have limited flexibilities in term of possible interconnectivity between components and do not necessarly provide the components to simulate load profiles. For the present study, exemple files were combined together to develop the model of the central cooling plant. This approach increased the time required to develop the model in EnergyPlus. TRNSYS, on the other hand, offers more flexibility in terms of system layout with a "drag and drop" approach to create the model.

Weather file, schedules and load profiles

In EnergyPlus the weather file must be entered in EPW format, while in TRNSYS weather data can be entered directly from measurements. The outdoor air wet-bulb temperature has a great influence on the performance of the cooling towers. Therefore, difference in wet-bulb temperature measured on site with the information available in the EPW file could explain some discrepancies in cooling tower performances. Perhaps modifying the EPW file with weather data measured on-site would lead to more accurate predictions of the cooling tower electricity use.

For schedules and load profiles, the use of external files is available for both program. However, EnergyPlus only accept hourly schedules, while any time step can be specified for schedules used in TRNSYS. In EnergyPlus, the simulation was run for a 15-minutes time-step with hourly average input data. By using hourly data, the peak load is reduced compared to the actual load on a 15 minutes basis. Also, this create discrepancies in operating schedule. For example, if chiller CH1 is started at 12:30, the hourly average information will actually start it at 12:00. This increases the discrepancies between the EnergyPlus simulation results and the actual measurements. As an example, if these discrepancies are eliminated for the cooling pumps P1 to P5, the R.E. drops to -0.3% compared to 16.0% as initially calculated (Table 8). For the seasonal eletricity use, the R.E. drops to 4.4%.

Chillers

The EnergyPlus model for the chillers is based on three empirical curves. The coefficients of the three curves were identified using measured data. The results from calibrated models have CV-RMSE for the electric power input lower than 15.3% compared to CV-RMSE of 16.1% for CH1 and 17.1% for CH2 when default models were used in the simulation.

For the TRNSYS model, two external files were used to model the chillers: (1) the chiller performance data file, which defines (i) the capacity ratio in kW/kW as the ratio between the chiller evaporator load at operating conditions, at given leaving chilled water and entering condenser water temperatures, and the load at design conditions; and (ii) the COP ratio as the COP at operating conditions divided by the design COP, and (2) the electric input part-load ratio (PWR) file in terms of cooling part-load ratio (PLR). The chiller performance default file that contains the capacity ratio and COP ratio for a combination of leaving chilled water and entering condenser water temperatures is required to have, for numerical purposes, at least two chilled water temperature and condenser water temperature points to characterise the performance of the chillers. In the central plant under study, the supply chilled water temperature is maintained constant at 6.7°C. Therefore, it is not possible to modify the first set of curves using measured data. Additional information was obtained from the manufacturer selection software for leaving chilled water temperature between 5°C and 9°C and condenser entering temperature between 16°C and 35°C to adjust the chiller performance data file. The electric input part-load ratio (PWR) file was adjusted using measurements. Obtaining the additional points from the manufacturer selection software is not always possible. Furthermore, only a limited number of points were provided by the chillers manufacturer to modify the TRNSYS default curves that characterise the performance of the chillers.

For the case under study, modifying the chiller model using only measured data was possible for the EnergyPlus chillers, while additional manufacturer data were required to modify the TRNSYS model. In terms of prediction accuracy, the results were similar for both softwares.

Cooling towers

The model for the cooling towers in EnergyPlus uses two empirical curves to determine the approach temperature and fan power at off-design conditions. An attempt to modify the approach temperature curve coefficients and design conditions with measured data was carried on using two different dataset: (1) a sub-set of measured data at the beginning of the summer, and (2) data over the complete summer season. However, the developped models did not converge and could not be used in the final simulation. This may be explained by the fact that the measured liquid-to-gas ratio is relatively low throughout the summer, varying between 0.85 and 2.79 for CT1 and 0.14 and 1.00 for CT2. A wider range of data might be required to identify the 27 curve coefficients properly. For the fan power at off-design conditions, modifying the curve coefficients using measured data did improved the simulation results: the R.E. was lowered by 22%.

In TRNSYS, the actual cooling tower models were not modified; however, two coefficients, the mass transfer constant (L/G), which is equal to the inlet water mass flow rate (kg/s) over the air mass flow rate (kg/s), and the mass transfer exponent (n) were modified using manufacturer data and sensitivity analysis (Monfet and Zmeureanu 2013). The control of the cooling towers was performed by varying the fan speed to maintain a constant cooling tower leaving water temperature using two correlations that estimate the VFD level of the fan developed using measured data.

Under the conditions of this study, the electric power input to the cooling towers was more accurately predicted by TRNSYS compared to EnergyPlus. However, the EnergyPlus cooling tower model allows the user to modify multiple parameters, while only a limited of parameters can be tuned to measured data in TRNSYS.

CONCLUSIONS

In this study, measured data were used to calibrate the EnergyPlus model of a central cooling plant. The results were compared (1) with data over the summer season, from 22 June to 20 September 2009; and (2) with prediction of a TRNSYS model of the same central cooling plant that was calibrated using measured data combined with manufacturer's information.

For the chillers, there is a fair agreement between measurements and predictions of water temperatures compared at key locations, with maximum RMSE of 0.8°C and the MBE varying between -0.2°C and 0.1°C for the EnergyPlus model.

For the electric power input to the chiller, the CV-RMSE is below 15.2%, while the NMBE is below ±6%. Overall, the calibration exercise showed fair agreement between the simulated and measured data, except for the electric power input to the cooling tower. On a seasonal basis, the simulation results for the central cooling plant from EnergyPlus and TRNSYS compared well with measured data. The R.E. are 10.8% and 5.5% for EnergyPlus and TRNSYS, respectively. For the simulation results obtained with EnergyPlus, half of this difference is explained by discrepancies in operating schedule.

A comparison between the approach undertaken to develop the EnergyPlus and TRNSYS input files as well as differences in the components model provided additional insight in terms of difference between the two simulation softwares.

For the EnergyPlus model, the interaction between the different loops was simplified by separating the two main equipment groups. Perhaps the use of Energy Management System object to control the operation of the loops would lead to a more accurate representation of the central cooling plant. Furthermore, additional attention should be given to the identification of the curve coefficients for the cooling tower approach temperature. This would improve the accuracy prediction in terms of peak power and energy use.

As a final note, the calibration approach proposed in this paper shows that it is possible to develop a calibrated model using measurements without modifying by trial-and-error some variables or using stochastic approaches.

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