MODEL-ASSISTED COMMISSIONING
OF A CHILLING PLANT

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Summary

The chilling plant of a large commercial building located in Brussels is currently submitted to repetitive commissioning.

The measurements are automatically taken by the Building Energy Management System. This system has been previously commissioned and can be considered as rather reliable.

A model is from long time available for simulating the whole plant. BEMS measurements available can easily be used to determine the main energy transfers inside this system, from the building towards the chillers and, finally, the cooling towers.

An almost continuous parameter identification of the chilling plant model has been done, during several years.

Several examples are presented in the paper, demonstrating, ab absurdo, how much a "model-assisted" continuous commissioning can help in deciding when a preventive maintenance should be done.

INTRODUCTION

The early design of the building considered here started some twenty years ago. At that time, very few of the potential occupants were interested to get air conditioning in their offices. Although the building simulation predicted high overheating risk, it was then decided to limit the full air conditioning to the meeting room and to the VIP offices. Most of other offices were designed with classical heating and mechanical ventilation.

The sizing of cooling equipment provocated some discussion among the different partners of the project. Some calculations were verified several time and some special measurements were performed in "parallel" with the official commissioning.

The building was officially inaugurated and fully occupied almost ten years ago. As a bad coincidence, just a few months later, when the cooling plant was not yet working correctly, the occupants were submitted to one of the hottest

summers of the century. Almost all of them became HVAC enthusiastic and it was therefore decided to prepare a progressive extension of the cooling to almost all the building zones.
These events, as well as further incidents, stimulated the interest of the building manager for some more commissioning work.

It was decided to extend the commissioning to the different levels of the system (plant, air handling units, air distribution network, terminal units, and occupancy zones), in order to track all cooling bottlenecks and overheating risks.

Still today the building may appear a little as an "extension" of our laboratory. Active visits are organized every year with several groups of students and some sort of "spot" commissioning is done during every visit. Several finishing school works and doctoral theses were based on that case study. At the end, a fair amount of data was accumulated during the last ten years. This ten-year story offers an interesting illustration of what could become a "continuous" commissioning process.

MODELLING OF THE COOLING PLANT

The model of the cooling plant was progressively developed during the first years of this commissioning, with both "simple global" and "more detailed local" views.

A simplified global model is used to represent the whole cooling plant (Figure 1). This model contains nine fluids "loops" interconnected (from the chilled water to the external air).
The main simplification consists in replacing each set of identical components (the five heat exchangers, the four ice storage tanks, the four chillers and the five cooling towers) by one equivalent component.

A first principle steady-state model is applied to each of component. This model is based on classical equations of transfer and conservation of mass and energy.
The (only-one equivalent) ice storage tank is represented as an equivalent heat exchanger with one (isothermal) side at 0°C.
This gives the following equations:

Loop 3 : ice storage.

$$\dot{Q}_3 = \dot{C}_3 \cdot (t_{31} - t_{21})$$

$$\dot{C}_3 = \dot{M}_3 \cdot c_2$$

$$\dot{Q}_3 = \varepsilon_3 \cdot \dot{C}_3 \cdot (0 - t_{21})$$

(simplified model of the ice storage system)

$$\varepsilon_3 = 1 - \exp(-NTU_3)$$

$$NTU_3 = \frac{AU_3}{\dot{C}_3}$$

$$AU_3 = 450 \ kW / K \quad (\text{hypothetical value; should be related to discharge and flow rate})$$

$$\dot{M}_3 = 0.1 \ kg / s \quad (\text{control variable})$$

The equilibrium bottle is characterized by an induction factor:

Loop 5 : equilibrium bottle.
Induction effect:

$$\dot{M}_5 = (1 + C_5) \cdot \dot{M}_{max,5}$$

$$\dot{M}_{max,5} = \textbf{Max}(\dot{M}_4, \dot{M}_6)$$

$$C_5 = 0.44 \quad (\text{induction factor experimentaly identified})$$

Mixings:

$$\dot{C}_5 \cdot t_{51} = \dot{C}_4 \cdot t_{21} + (\dot{C}_5 - \dot{C}_4) \cdot t_{41}$$

$$\dot{C}_5 \cdot t_{41} = (\dot{C}_5 - \dot{C}_6) \cdot t_{51} + \dot{C}_6 \cdot t_{62}$$

$$\dot{C}_5 = \dot{M}_5 \cdot c_2$$

$$\dot{C}_6 = \dot{M}_6 \cdot c_2$$

$$\dot{M}_6 = \frac{134}{4} \ kg / s \ (\text{if one chiller in use})$$

Each evaporator and condenser is also considered as semi-isothermal heat exchangers:

Evaporators:

$$\dot{Q}_{6,7} = \varepsilon_{6,7} \cdot \dot{C}_6 \cdot (t_{61} - t_{ev})$$

$$\varepsilon_{6,7} = 1 - \exp(-NTU_{6,7})$$

$$NTU_{6,7} = \frac{AU_{6,7}}{\dot{C}_6}$$

$$AU_{6,7} = \frac{717}{4} \ kW / K \quad (\text{with one chillers in use})$$

$$\dot{Q}_{6,7} = \dot{M}_7 \cdot (h_{71} - h_{74}) \qquad \text{etc.}$$

The (only-one equivalent) compressor is characterized by its (supposed-to-be constant) isentropic and volumetric effectiveness:

$$\dot{M}_7 = \frac{\dot{V}_{71}}{v_{71}}$$

$$\dot{V}_{71} = x_{sv} \cdot \dot{V}_s$$

$$x_{sv} = 1$$

(if control slide vane fully open)

$$\dot{V}_s = \frac{0.942}{4} \text{ m3 /s } \text{ (total with 1 chiller in use)}$$

$$v_{71} = v\,(\text{'R22'}, T = T_{71}, P = P_{ev})$$

$$\dot{W}_7 = \eta_m \cdot \dot{W}_{el,7} \text{ (shaft power)}$$

$$\eta_m = 0.9 \text{ (efficiency of electric motors; hypothesis)}$$

$$\dot{W}_{el,7} = \dot{M}_7 \cdot \frac{w_s}{\varepsilon_s}$$

$$\varepsilon_s = 0.675 \text{ (average value for the 4 chillers)}$$

The (only-one equivalent) cooling tower is characterized by a set of fictitious heat transfer coefficients, each one corresponding to a given fan regime:

$$\dot{Q}_{8,9} = \varepsilon_{8,9} \cdot \dot{C}_{min,8,9} \cdot (t_{81} - t_{93})$$

$$\dot{C}_{min,8,9} = \text{Min}\,(\dot{C}_8, \dot{C}_9)$$

$$\dot{C}_9 = \dot{M}_9 \cdot c_{pf}$$

$$\dot{M}_9 = 89 \text{ kg /s}$$

$$c_{pf} = \frac{h_{91} - h_{93}}{t_{91} - t_{93}}$$

$$\varepsilon_{8,9} = \frac{1 - \exp\left[-NTU_{8,9} \cdot (1 - \omega_{8,9})\right]}{1 - \omega_{8,9} \cdot \exp\left[-NTU_{8,9} \cdot (1 - \omega_{8,9})\right]}$$

$$NTU_{8,9} = \frac{AU_{8,9}}{\dot{C}_{min,8,9}}$$

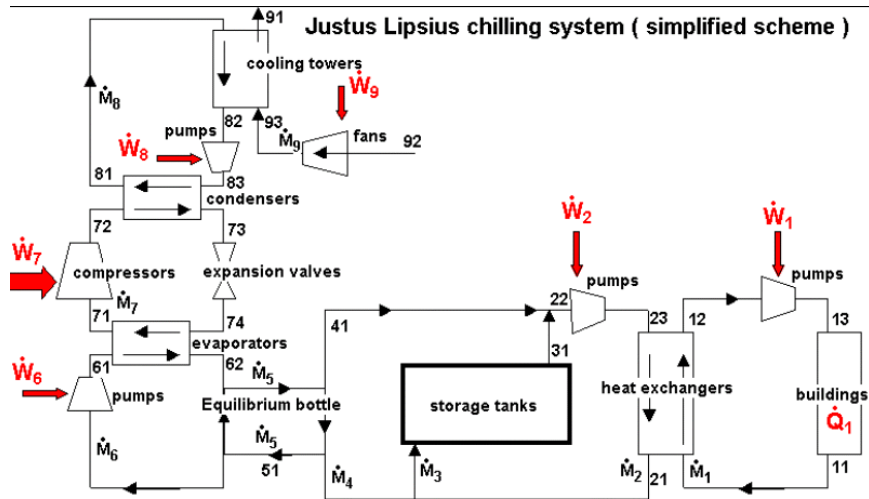$$AU_{8,9} = AU_{ct} \cdot \frac{c_{pf}}{c_p}$$

etc.

Figure 1 : Simplified model of the cooling plant

Fluids temperatures are measured at many points. An print screen example of measuring result is presented in Figure 2. It's a synthetic presentation, directly corresponding to the synthetic schema of Figure 1.

On Figure 2 are given, not only the fluid temperatures, but also the chilled water enthalpy flow rates (for both buildings), the liquid level in the expansion vessel of the ice storage system and the status of all controlled devices (valves, pumps, compressors and fans).

The following variables are recorded by the BEMS :
- Cold water enthalpy flow rate (corresponding to the "useful" cooling power produced by the plant);
- Frequencies supplied to the motors of the cold water pumps;
- Status of the ice storage system (liquid level in expansion tubes);
- Condensers and evaporators pressures on refrigerant side;
- Electrical currents provided to chillers motors;
- Positions of the sliding vanes of the chillers compressors;
- Positions of glycol-water valves;
- Status of all electric motors (pumps and cooling towers fans).

The electrical consumptions of all electric motors are not automatically recorded by the BEMS, but they can be read on plant control panels.

Not all the measuring points have the same accuracy and the same value. Many of the temperatures are only used as redundant checking information.

At early re-commissioning time, every temperature measuring point has been submitted to a careful evaluation (actual position of the sensor, actual signal, conversion law …) and a hierarchy has been established among all variables actually recorded.

With that information and with the help of the simple model of Figure 1, an "energy picture of the installation" is easy to draw at any time:
The enthalpy flow rate "transported" across each of the circuits identified in Figure 1 is determined by energy balances, starting from the cold water circuits, where the enthalpy flow rates are directly measured and going back "up-stream" towards the chillers and the cooling towers.
For example:

Loop 1 : buildings cold water supply.

$$\dot{Q}_1 = \dot{C}_1 \cdot (t_{11} - t_{13})$$

$$\dot{C}_1 = \dot{M}_1 \cdot c_1$$

$$c_1 = 4.18 \; kJ / kg * K$$

$$t_{11} = 12.7 \; °C \quad (\text{ simulation input })$$

$$t_{13} = 7.2 \; °C \quad (\text{ control set point })$$

$$t_{12} = t_{13} - \frac{\dot{W}_1}{\dot{C}_1}$$

$$\dot{W}_1 = 32.37 \; kW$$

$$\dot{Q}_{1,2} = \dot{Q}_1 + \dot{W}_1$$

$$\dot{Q}_{1,2} = \varepsilon_{1,2} \cdot \dot{C}_{min,1,2} \cdot (t_{11} - t_{23})$$

$$\dot{C}_{min,1,2} = \mathbf{Min}(\dot{C}_1, \dot{C}_2)$$

etc.

This can be done automatically on the basis of the BEMS recordings or "by hand" on the basis of BEMS instantaneous "print-screens".
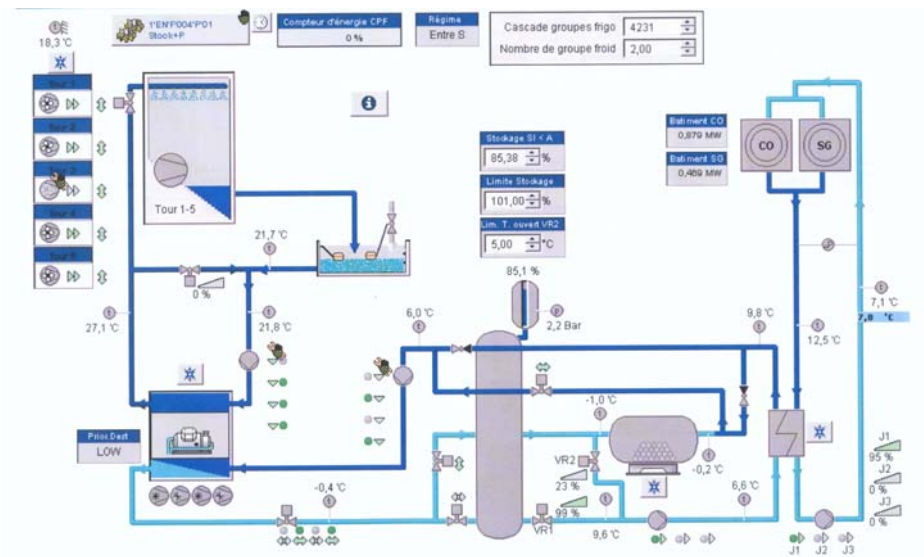
Figure 2:**Example of synthetic information provided by the BEMS**

The many continuous recordings and also the many spot verifications should have permitted to detect diagnose and resolve on time most of the problems encountered with this installation. "Should", if that information had been sooner and more systematically used.

Some of the problems encountered are shortly described hereafter.

1. Lack of cooling capacity

The chillers installed in this building did never reach their nominal cooling capacity.

A first default was easy to diagnose: the electrical current threshold value was originally set at a too low level.

But, even after having removed this artificial limit, it was discovered that the chillers were not able to give more than 80% of their nominal capacity.

Of course, a more careful initial commissioning would have permitted to identify this default on time.

It's indeed a rather easy task to tune the chiller model on the basis of manufacturer data and to compare the output of this model with measuring results.

With the twin screw compressors used here, nominal swept volume and isentropic effectiveness appear as rather conservative characteristics in all regimes considered.

2. Refrigerant leakage

A large amount of (R22) refrigerant was consumed during the first years. Important leakages occurred across the shafts seals.

The effect of a lack of refrigerant is a reduction of cooling capacity, which is detected as indicated hereabove.

3. Sticky check valves

Inspecting the distributions of all fluids temperature was found to be an easy way to detect a sticky check valve: it gives "parasitic" mixings due to fluid re-circulation (an unused pump may then rotate in reverse direction, as a turbine).

This was, among others, observed several times in the warm water circuit which is connecting the condensers to the cooling tower. This circuit is very polluted by the (direct contact) cooling tower.

4. Ruine of the ice storage system

The ice storage system consists in a set of four reservoirs filled by plastic modules containing water. These modules are surrounded by glycol-water. After a few years of use, it was discovered that most of the modules were broken. This reduced dramatically the energy capacity of the system.

Again here, a more systematic analysis of the temperatures and corresponding enthalpy flows would have helped a lot in detecting much earlier this dramatic event.

Two indicators can be used to detect this failure:
1) the liquid level in the expansion vessel of the ice storage system can be correlated with the actual amount of energy actually accumulated;
2) the global heat transfer coefficient is easy to identified and easy to compare with manufacturer data.

5. Fouling of the cooling towers

As other ones, this failure was discovered much too late and gave a beautiful "ab absurdo" demonstration about the usefulness of continuous commissioning…

In June 2002, a student work, performed with previous BEMS recording, made appear a "strange" behaviour of the cooling towers:

Everything was occurring as if their heat transfer coefficients were reduced by 50 to 70% !

Interesting but much too late discovery: a bad coincidence made that June 18, 2002 occurred to be one of the hottest days of the century; the cooling plant capacity was then dramatically reduced. This caused very strong (and expensive) perturbations in the activities inside the building.

The diagnosis was later confirmed by the maintenance : the cooling towers were tapped by a mix of dust and calcium carbonate in such a way that water circulation and air flow rate had to be severely altered.

BEMS data analyses, performed before and after maintenance, confirmed how an early detection of this failure had been easy.
A preventive maintenance could have been decided on time.
Examples of results are presented in Figures 3 and 4. The cooling towers model can be used by assuming that the water and airflow rate remain unaltered and by identifying the heat transfer coefficient.

This is done with a sample of BEMS records in Figures 3: instantaneous values of heat flow rate, water flow rate and "dry" heat transfer coefficient are here plotted in almost instantaneous values (every 15 minutes) on the basis of the measurements automatically recorded by the BEMS.
The reduction of heat transfer coefficient is very spectacular: it's floating between 10 and 20 kW/K, i.e. far below its nominal level of 70 kW/K!

The effect of this reduction of heat transfer coefficient is also spectacular when observing the behaviour of the whole system working in full load, in hot weather conditions: the sliding vane is then reducing the cooling capacity in order to protect the electric motor of the compressor. This can be observed in the reality and in the simulation.
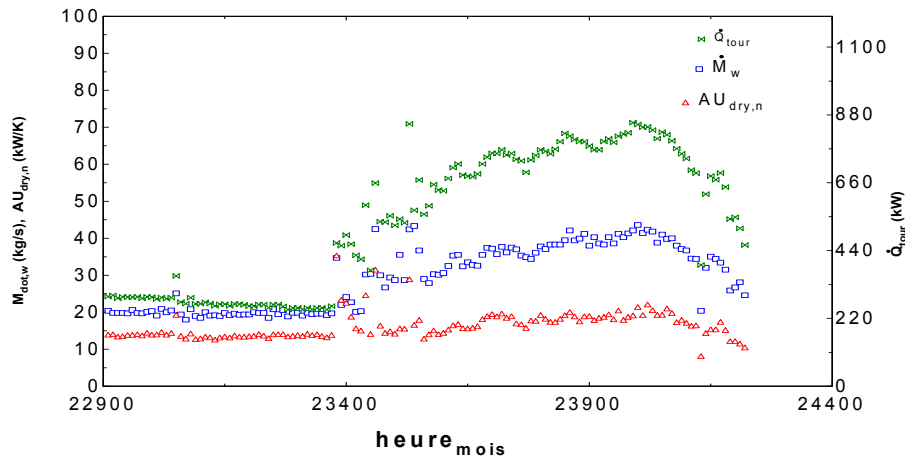

Figure 3: Sample of information extracted from BEMS recording

6. Fouling of the condensers

The condensers are exposed to almost the same fouling as the cooling towers. It's therefore important to track carefully the heat transfer coefficients of the condensers.

Very significant differences were observed between the values identified before and after maintenance.

But the detection by simulation is here a little more delicate: the semi-isothermal model appears sometime as too crude: a three-zone model (taking both de-superheating and sub-cooling into account) may help a lot…

CONCLUSIONS

There is no excuse for not being able to detect on time most of the performance degradations occurring in a classical cooling plant.

Simple and accurate simulation models are available. They are easy to tune, on the basis of manufacturer data and of "as built" files.

Such pre-tuning would help a lot, when having to conduct the initial commissioning.

A more or less continuous re-tuning should be automatically performed by computation of BEMS data, in such a way to detect the performance degradations and to select the best time for preventive maintenance.

There is here a great future for simulation.

BEMS *and* Model assisted continuous commissioning should become very soon a cost-effective business.

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