SIMULATION - ASSISTED AUDIT OF AN AIR CONDITIONED OFFICE BUILDING

Stephane Bertagnolio
Research Assistant

Jean Lebrun
Professor

Jules Hannay
Research Engineer

Cleide Aparecida Silva
Research Engineer

Thermodynamics Laboratory
Aerospace and Mechanical Engineering Department
University of Liege, Belgium

ABSTRACT

The case study presented here concerns the audit of a typical, medium-size, office building erected in Brussels at the end of the sixties. This building is equipped with a classical old fashioned air conditioning system composed of air handling units and four-pipes induction units.

In the first part of the paper, a classical audit procedure is applied. It consists in a systematic analysis of all information available, with help of very simple calculation.

In the second part of the paper, an equation-based building-HVAC simulation tool is used to assist the audit.

Fuel and electricity consumption are then interpreted and significant energy saving opportunities are identified.

INTRODUCTION

Environmental concerns and the recent increase of energy costs open the door to innovative techniques to reduce energy consumptions. Buildings represent about 40% of the European energy consumption. Non-residential buildings are part of the main energy consumers and improvement of their energy performance is a major challenge of the 21th century. To this end, the European Commission approved the European Directive on Energy Performance of Buildings (EPBD, 2002) on 16 December 2002.

To promote improvements in the HVAC installations of existing buildings, the article 9 of the EPBD directive establishes mandatory audits and inspections of air-conditioning systems.

Four audit stages are generally distinguished (AUDITAC, 2007):

1. The "benchmarking" helps in deciding if it is necessary to launch a complete audit procedure; it's based mainly on energy bills and basic calculations. Simulation is then of great help to define some, even very provisory, reference performances (or "benchmarks"), in view of a first qualification of the current building performances.
2. The aim of the "pre-audit" (also called "Walk-through Audit" or "Inspection") is to identify the main defects and "energy conservation opportunities" (ECO's). Its results are supposed to orient the future "detailed" audit. The inspection consists in a visual verification of HVAC equipment, in an analysis of operating data records and in a systematic disaggregation of recorded energy consumptions. A "baseline" calibrated simulation model can be used to identify the main energy consumers (lighting, appliances, fans, pumps, chiller, …) and to analyse the actual performance of the building.
3. The "detailed" audit consists in a detailed and comparative evaluation of the ECOs previously selected. At this step even more, simulation is the key tool.
4. The "investment grade" audit concerns the detailed technical and economical engineering studies, justifying the costs of the retrofits. This fourth audit stage brings the system (building + HVAC) to a new life cycle: new design, call for tenders, submissions, evaluations, installations, commissioning, etc.

The work presented here is performed in the frame of the European "HARMONAC" project (HARMONAC, 2008). The example of case study presented here concerns a typical air-conditioned office building built in Brussels at the end of the sixties.

In the first part of this paper, the building and its HVAC are described and a classical audit procedure is used to analyse the recorded data. Some simulation tools are then used to go deeper in the analysis of the performances of the installation. Finally, some significant retrofit opportunities are proposed.

BUILDING DESCRIPTION

Building design

The considered building is an existing medium-size office building (around 26700 m² of air-conditioned floor area), erected in Brussels at the end of the sixties (Lebrun et al., 2006). The building is composed of three blocks, has a “H” shape (figure 1) and is North-South oriented. Eight storeys of the building include landscaped offices and meeting rooms. The five underground levels are dedicated to cars parking.

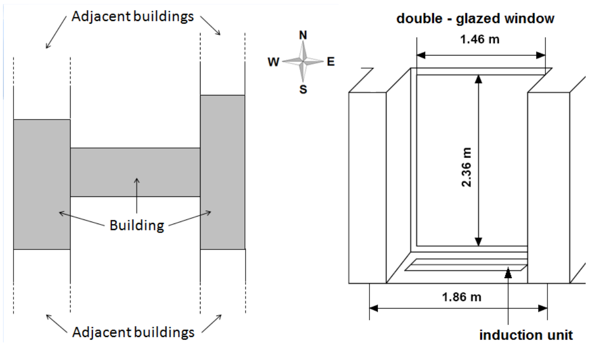

Figure 1: Case study building (left) and envelope module (right)

The frontages of the lobby are made of single-glazed windows. The rest of building envelope is made of about 1000 double-glazed modules, equipped with external solar protection (figure 1). The main characteristics of the envelope are given in table 1.

Table 1: Main characteristics of the building

Case Study Building		
Conditioned floor area	*[m²]*	26700
Number of storeys	*[-]*	9
Building height	*[m]*	30
Main orientation	-	N/ S
Geographical location	-	Brussels
External walls area	*[m²]*	7090
Number of occupants	*[occ]*	1100
Lighting power	*[W/m²]*	15
Appliances power	*[W/m²]*	20
Opaque frontages area	*[m²]*	2570
Opaque frontages U value	*[W/m²-K]*	1.15
Roof deck area	*[m²]*	2970
Roof deck U value	*[W/m²-K]*	0.32
Double-Glazed frontages area	*[m²]*	3020
Double-Glazed windows U value	*[W/m²-K]*	3.6
Single-Glazed frontages area	*[m²]*	1440
Single-Glazed windows U value	*[W/m²-K]*	5.8

HVAC system

About 1000 four-pipes heating and cooling induction units are installed in the offices. The CAV Air Handling Units provide together a total of about 190000 m³/h of fresh air per hour, 75 hours per week, to the conditioned zones (from level 0 to 8). Vitiated air is rejected in the underground storeys to ensure ventilation of the parking. This ventilation flow rate corresponds to about 2.4 air renewals per hour. According to the weather conditions, the supplied air can be heated and adiabatically humidified, or cooled and dehumidified.

Heat production is ensured by four fuel-oil boilers, giving together a nominal heating capacity of about 4 MW. Chilled water production is ensured by four water cooled chillers, coupled to two cooling towers, giving a total cooling capacity of about 2.1MW.

Occupancy and operating profiles

The building is occupied by about 1100 people, between 8 am and 18 pm, 5 days per week. The ventilation is maintained approximately 75 hours per week. Electrical appliances and artificial lighting are switched on between 7 am and 21 pm from Monday to Friday. Temperature and humidity setpoints are maintained between 8 am and 20 pm. The operating and occupancy profiles are summarized in Figure 2.

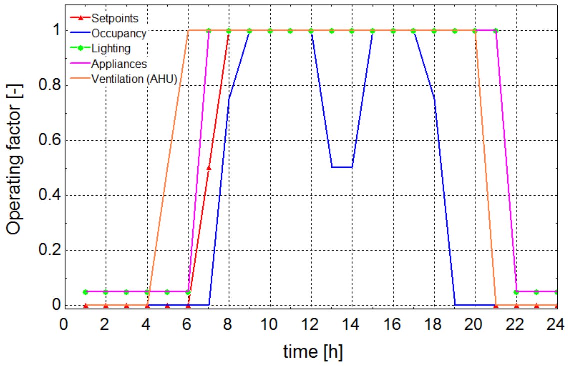

Figure 2: Typical day operating profiles

Nominal heat losses

Using the information given in table 1, the global heat transfer coefficient of the whole envelope can be estimated as follows:

$$AU_{envelope} \approx 23\ [\frac{kW}{K}]$$

Another heat transfer coefficient corresponds to the mechanical ventilation:

$$K_{vent} \approx 64\ [\frac{kW}{K}]$$

In nominal heating conditions (outdoor : -10°C/RH 90%; indoor : 20°C/RH50%), with $\Delta t = 30$ K, this gives a sensible power demand of:

$$\dot{Q}_{s,nom} = \left(23[\frac{kW}{K}] + 64[\frac{kW}{K}]\right) * 30[K] \approx 2600\ [kW]$$

If having to maintain 50% of relative humidity at 20 °C in the same nominal conditions the corresponding latent heat demand would be of about:

$$Q = [w(20°C; 50\%) - w(-10°C; 90\%)] * 2.5E3[\frac{kJ}{kg}] \approx 14.5\ [\frac{kJ}{kg}]$$

i.e. 920 kW in the present case; this would bring the total heat demand around 3.52 MW. This very rough estimate of the total heat demand can be compared to the power installed in the heating plant (around 4 MW): the agreement is not bad and there seems to remain a fair reserve of heating power.

Nominal heat gains

The envelope and ventilation heat transfer coefficients identified in heating mode could also be used for heat gains calculations. In nominal cooling conditions (outdoor : 30°C/RH 50%; indoor : 25°C/RH50%), with $\Delta t = 5$ K, the sensible cooling power demand is estimated to 430 kW.

Other sensible heat gains are coming from sunshine, occupants (sensible) metabolism and electricity consumed inside the building.

Solar heat gains are here very reduced, thanks to efficient external solar protection. They are estimated to no more than 50 W/m2 of window area, i.e., for the whole glazed area (4 460 m2), around 220 kW.

The sensible metabolism of 1100 occupants is also a limited contribution and is of about 80 kW. The electricity consumed inside the building dominates this sensible heat balance and is estimated to about 800 kW. Consequently, the total sensible heat gains were estimated to 1.53 MW.

The latent cooling demand associated to air drying had to be added. This term is estimated to:

$$Q = [w(30°C; 50\%) - w(25°C; 50\%)] * 2.5E3[\frac{kJ}{kg}] \approx 8.6\ [\frac{kJ}{kg}]$$

i.e. 540 kW, bringing the total cooling demand around 2.07 MW. A satisfactory agreement is found between this rough estimation and the cooling power actually installed in the building (2.1 MW).

Control strategy

The building is equipped with a classical BEMS with two levels: a set of local control units and a PC for supervisory management.

For all the office zones, the dry bulb temperatures are controlled in feedback, thanks to about 500 double thermostatic valves: these valves are modulating the water flow rates supplying the heating and cooling coils of the induction units.

The air humidity control is achieved in the AHU, thanks to a (on/off) control of the pump supplying the adiabatic humidifier and to a modulating valve supplying the cooling coil. There is also a feed back control of the mixing valve supplying the pre-heating coil; the AHU exhaust air temperature set point is displaced in relationship with the outside air temperature, in such a way to make the adiabatic humidification possible, when required, and also to bring some sensible heating or cooling to the zone, when required.

The primary air is only supplied during pre-heating and occupancy time.

Out of that time, if the weather is very cold, the induction units are still used in free convection mode, by supplying hot water to the heating coils.

The re-starting time of the installation in the morning is fixed by the BEMS, according to weather conditions and to the week day.

In average, the total running time is of about 75 h/week.

The chilled water temperature regime is 6/12 °C in nominal conditions.

Fans and air distribution network

The as-built files (completed by a quick inspection) give a fair estimate of all ventilation airflow rates.

According to that information, the total fresh airflow rate supplied in the whole building is of about 170 m³/h per occupant, when the building is fully occupied.

But this fresh air is supplied on 75 h per week, although the building is fully occupied 50 h per week, only. This means that, in average, the building is supplied with an average rate of 255 m³/h per person!

The energy impact of such generous ventilation is triple:

1. It increases the sensible and latent energy consumed to bring the fresh air to required temperature and water content;
2. It increases the fans consumptions;
3. It increases the internal loads, almost in proportion to the fans consumptions.

By supposing a global fan efficiency of about 75%, the total electricity demand of the fans is of the order of 214 kW, i.e. of about 8 W/ m2.

RECORDED DATA ANALYSIS

Monthly records of fuel consumptions are available from 1971 to 2006 and monthly records of electricity consumption are available from November 2004 to February 2006. The records made from November 2004 to February 2006 are plotted in Figure 3.

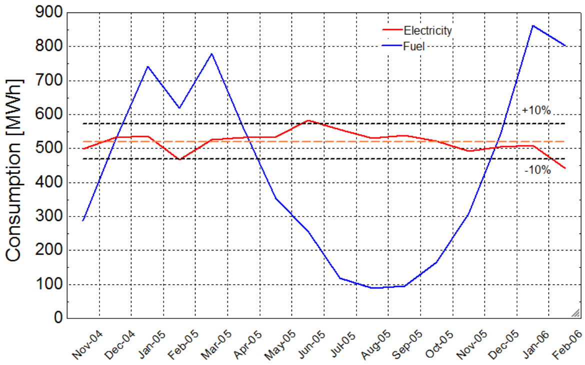

Figure 3 : Electricity and Fuel Consumptions

The average electricity consumption of this period is floating around 520 MWh/month ± 10 %. No seasonal variation is noted.

The fuel oil energy consumption shows much larger variations, around an average of 440 MWh/month.

Figure 4 shows the distribution of fuel oil power defined in montly average (from January 2004 to March 2006), as function of the external dry bulb temperature.

This thermal signature allows to identify a meaningful linear regression. The plotted linear regression shows that the heating demand tends to zero when the outside temperature is around 23°C.

The slope of this law (about 49 kW/K) should be of the same order of magnitude as the average heat transfer coefficient of the building. In order to calculate an average heat transfer coefficient, it is necessary to take the ventilation intermittency into account. This gives:

$$K = 23\,[\frac{kW}{K}] + 64\,[\frac{kW}{K}] * \frac{75}{168} \approx 52\,[\frac{kW}{K}]$$

The two values are in good agreement and confirm that the fuel consumption is quite well explained.

Theoretically, it should have been a little higher, because of the latent heat power consumed to humidify the air which is not taken into account in this average heat transfer coefficient. The remaining error found in this building "signature" is very probably due to the effect of the inside temperature control (the temperature inside the building is "sliding" down slowly with the outside temperature).

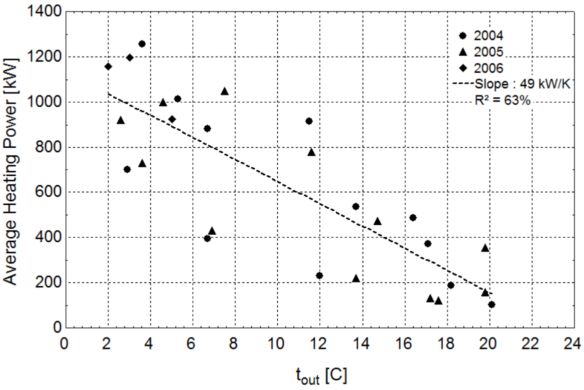

Figure 4 : Building Thermal Signature

The dispersion of the recorded points and the poor correlation coefficient (R²=63%) are explained by the fact that the fuel consumption is not only influenced by the outdoor temperature but also by other parameters. The other influences could be:

- The solar gains;
- The heterogeneous use of HVAC equipment (due to variable comfort requirements, variable occupancy rate, variable internal loads,…);

However, considering the fact that the building is equipped with very efficient solar protections, the first influence can be neglected and the discrepancies in the recorded data should be due to the variable occupancy, variable internal loads associated and variable way of using the HVAC system.

The interpretation of the electrical consumption is much more difficult. A very first step is to distinguish the peak hours and off-peak hours consumptions. But both orders of magnitude are very high: they correspond to 22 and 34 W/m2 of conditioned floor area!

The difference between these two power levels can be explained by a much higher rate of use of the HVAC system during peak hours.

Indeed, the peak supplement is of the same order of magnitude as the total fan power (about 8 W/m²), which should be the most important contribution in the HVAC electrical consumption.

The very high electricity consumptions are probably (but not completely) due to the computation and lighting equipements.

As seasonal variations are insignificant, it is not possible to identify the impact of the chillers. More detailed records would be required to go further in this analysis: hourly records and/or separate records for HVAC and non-HVAC consumptions.

USE OF SIMULATION TOOLS

As mentioned before, building energy simulation tools are very useful at the different steps of an audit procedure.

At benchmarking stage mainly, the simulation tools have also to be usable with a limited quantity of information only, depending on data actually available. These tools must be easy-to-use, transparent, reliable, sufficiently accurate and robust.

To this end, two building energy simulation tools have been developed in the frame of both AUDITAC and HARMONAC projects (Bertagnolio and Lebrun, 2008).

The first one, called “BENCHMARK”, is used to compute the "theoretical" (or « reference ») consumptions of the building, supposed to be equipped with a “typical” HVAC system, including air quality, temperature and humidity control. The building is considered as a unique zone, described by very limited number of parameters. This first simulation tool should help the auditor in getting, a very first impression about the performances of the system and very first interpretation of the recorded consumptions.

The second one, called “SIMAUDIT”, offers a larger range of available HVAC equipment. The building is still considered as a unique zone but is coupled to a more realistic HVAC system, representing the actual one. After having been calibrated to the recorded data, the baseline model can be used to identify the main energy consumers (lights, appliances, fans, pumps, …) and to analyse the actual performance of the building.

The simulation tools have similar modelling bases and include models of both the building and the HVAC equipment (Air Handling Unit, Terminal Unit, heat and cold production systems, distribution networks,...). These models are submitted to different loads and interact at each time step with a simplified control module (Figure 5).

The main phenomena involved in building dynamics are taken into account in such a way to compute realistic heating and cooling demands. Indeed, the indoor conditions of the zone come from the equilibrium established among many different influences.

A compromise is made between the number of influences taken into account and the simplicity of the model: transient heat transfer through walls, energy storage in slabs, internal generated gains, solar gains through windows, infrared losses and, of course, ventilation and heating/cooling devices, are actually taken into account.

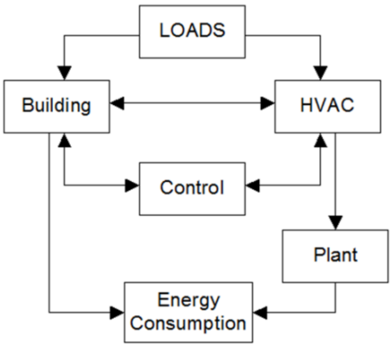

Figure 5: Model block diagram

The outputs, inputs and parameters are selected according to the specific needs of the user (Figure 6).

The main outputs of the tool are :

- Air quality and hygrothermal comfort achievements : CO2 contamination, temperature, humidity, PPD and PMV indexes
- Power distribution and energy consumptions (Fuel and Electricity)
- HVAC components specific demands

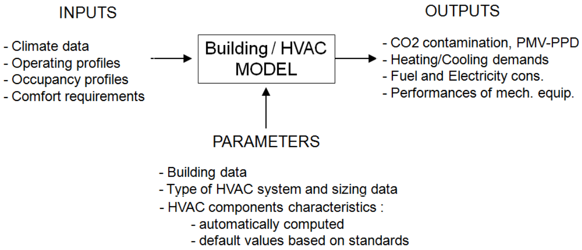

Figure 6 : Inputs, Outputs and parameters of the software

The main inputs (provided in tables) are :

- Weather data : hourly values of temperature, humidity, global and diffuse radiations
- Nominal occupancy loads (in W/m²), occupancy rates
- Comfort requirements: air renewal, temperature and humidity set points
- HVAC installation functioning rates
- Control strategies and set points: feedback on indoor temperature and relative humidity, feedforward on occupancy schedules and calendar.

The main parameters are :

- Dimensions, orientation and general characteristics of the building envelope (e.g. "heavy", "medium" or "light" thermal mass and walls U values).
- Sizing factors of the main HVAC components

The other parameters of the model, as HVAC system characteristics and nominal performances and capacities can be automatically computed through a pre-sizing calculation or defined basing on default values given in European standards (prEN 13053 and 13773).

The implementation of this global building-HVAC model in an equation solver (Klein, 2002) and its validation have been respectively discussed by Bertagnolio and Lebrun (2008) and Bertagnolio et al. (2008).

Benchmarking

The first software presented above ("BENCHMARK") is applied to the nine conditioned storeys of the building (from level 0 to 8), simulated as a unique zone. Parking zone is not considered in the study. The actual characteristics of the building envelope, the estimated internal generated gains, the actual occupancy schedules and temperature and humidity setpoints are entered in the software. The first approach consists in supposing that the studied building is coupled to a "typical" HVAC system (very different of the actual one) ensuring efficient air quality, temperature and humidity control. The performances of this system (pressure drops and HVAC components efficiencies) are estimated according to the standards prEN 13053 and 13773. The constant hygienic ventilation flow rate is fixed to 45 m³/h of fresh air per hour and per occupant; the AHU is supposed to be equipped with a classical cross-flow heat recovery system.

This first simulation run gives the results plotted in Figure 7 and 8. To allow a fair comparison between measured and computed data, monthly fuel consumption records are here averaged on the 30 years of available data. This method tends to minimize the discrepancies due to the use of only one typical meteorological year data set in the simulation. For electricity consumption, the values of 2005 are used as reference.

It appears that monthly computed and measured consumptions are very different. Mostly the fuel, but also the electricity consumptions are largely underestimated by the software. This suggests the existence of important energy savings potentials.

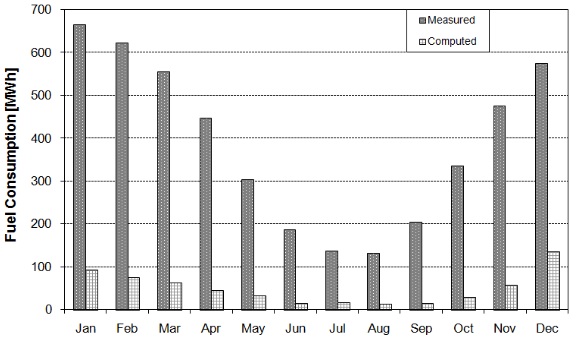

Figure 7 : Measured and computed fuel consumptions (first run)

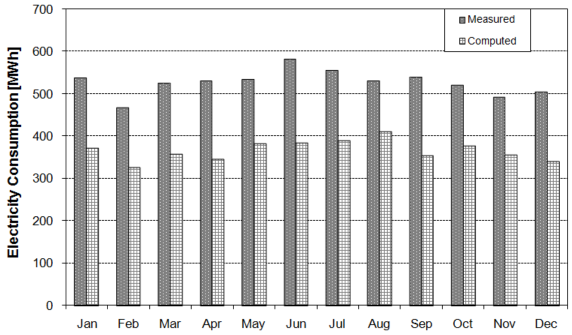

Figure 8 : Measured and computed electricity consumptions (first run)

Calibration and analysis

In this second phase of the study, the second tool ("SIMAUDIT") has to be used. This second allows to simulate the behaviour of the actual installation with more accuracy.

With more realistic hypotheses (much higher ventilation flow rate) and a description of the actual HVAC system (four-pipes induction units, no heat recovery system,...) and its performances and operating conditions, the software gives the results shown in Figure 9. The computed and measured monthly consumptions are now in much better agreement.

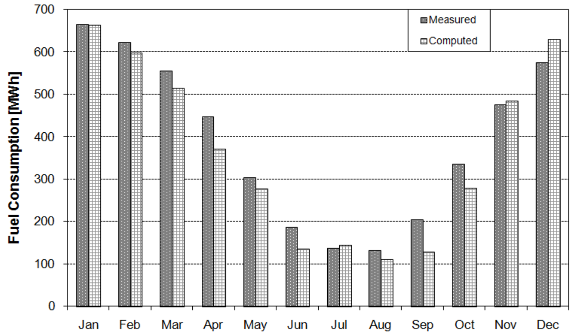

Figure 9 : Measured and computed fuel consumptions (after calibration)

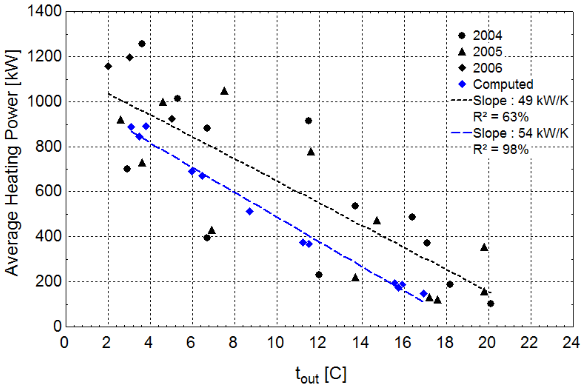

Figure 10 : Computed and Recored Thermal Signatures

The thermal signature generated by the software can be compared to the one based on recorded data (Figure 10). The slope of both recorded and computed signatures, respectively 49 and 54 kW/K, are similar and in good aggreement with the building global heat transfer coefficient estimated here above (53 kW/K). The computed thermal signature has a better correlation factor (R²=98%). This indicates that, with strictly well defined occupancy, corresponding internal gains and hypothetical and simplified HVAC control, the fuel consumption is mainly correlated with the outdoor temperature. So, as supposed above, the discrepancies observed with the recorded data should be mainly due to the variations in occupancy rate, internal gains and control strategy.

After having been calibrated, the tool can be used to disaggregate the electricity consumption and to identify the main energy consumers (Figure 11). This indicates that an important part of the electricity consumption is due to lighting and appliances. Fans and pumps are in charge of about 22 % of the global electrical consumption, while chiller part is only of about 10 %.

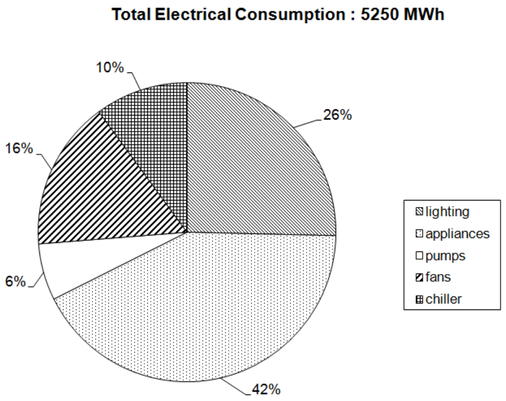

Figure 11 : Disaggregation of computed electricity consumption

RETROFIT OPTIONS

Some retrofits were already made on the plant and on the AHU's. The replacement of existing induction units by more efficient devices (new induction units or fan coils, if fitting in the small space available) should make possible to run the system with higher chilled water temperature and therefore better chiller COP.

Many other retrofit opportunities can already be identified:

1. A better fresh air management is certainly achievable. The air renovation time period could be reduced from 75 h to 50h per week, in order to fit with the full occupancy. In heating period, the night set back of the thermostat is here uneconomical: it's much better to shut down the primary air supply and to use the induction units in static heating mode. From other part, the primary air flowrate migth be reduced in mid season, according to the actual cooling demand of the offices.
2. A direct energy recovery system might be installed between supply and exhaust air circuits.
3. Some air re-circulation would be welcome, whenever the induction units require more primary air than what is needed for indoor air quality.
4. Variable speed might help in reducing fans and pumps consumptions.
5. Variable chilled water temperature might also be introduced.
6. The possibility of using such installation in free chilling mode (i.e. with production of chilled water by the cooling towers only) should be always considered. Actually, an attempt of free chilling was even done sometime ago, by adding a water-to-water heat exchanger between the condenser and the evaporator circuits (in parallel to the chillers). For reasons which couldn't be found back, this experience failed and the system was dismanteled!
7. An optimal control of cooling towers should allow to reduce the electrical consumption of their fans.
8. A more careful analysis of the space and time distributions of heating and cooling demands would help in identifying the opportunities of heat pumping and reversible air conditioning:

- During almost all the heating season, the extracted air represents a “free” heat source of more than 600 kW for a heat pump, whose evaporation temperature would be fixed around 5°C.
- The air-cooled condensers of the auxiliary chillers, used all the year for the data processing offices, are other free heat sources.

This last retrofit opportunity is studied in details in the frame of the IEA-ECBCS Annex 48 project (“Heat Pumping and Reversible Air Conditioning”).

More detailed calculations are required to go further in this analysis and to select the most attractive retrofit opportunities.

Adapted simulation models are badly needed at this stage. Such models are still under development in the frame of the HARMONAC and IEA-ECBCS Annex 48 projects.

CONCLUSION

In this case study One of the main difficulties comes from the too many lacks of information. Filling these lacks would require, more detailed energy records on site and more detailed information about the actual installation.

However, monthly energy bills and quick inspections allow a first and rough analysis of the behaviour of the building and of its HVAC system.

Simulation models are used to allow a better interpretation of the available data. Differente models of HVAC equipment are used at different stages of the energy audit. The most simplified models with very few parameters are of great help for benchmarking purposes. They allow the auditor to get a first impression about energy saving potentials.

Then, calibrated but still simplified simulation models are used to disaggregate the electricity consumption and to allow a better interpretation of on site records.

Finally, more detailed and specific simulation tools should be used to allow a safe identification and an assessment of the most promising retrofit opportunities.

ACKNOWLEDGMENT

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