Use of a Global Building-HVAC System model for Audit

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ABSTRACT

A hourly dynamic simulation tool for building and HVAC system is presented in this paper. The paper intends to show how a simplified simulation model can help in the audit of a HVAC system. The work presented here began in the frame of the European “AUDITAC” project and is continued in the frame of the WP7 (“Improved inspection and audit modelling tools”) of the “HARMONAC” project.

Better than looking for an hypothetical global weather index, similar to degree-days, it seems more rational to run a simulation model on a complete typical year to establish the energetic profile of a building and its HVAC system. At least in first approach, the whole building can be seen as a unique zone, cooled or heated by a complete HVAC system controlled with simple control strategies.

To make such tool usable by an auditor, the quantity of inputs must be very limited. The model requires only a brief description of the building and the related HVAC system. The bases of the modelling are presented here.
1. INTRODUCTION

In the frame of a pre-audit procedure, an experimental identification of the building heating, cooling and electricity consumptions is usually almost impossible. Indeed, heat/cool counters and separated electrical counters are rarely installed in buildings. Auditors encounter much problems in distinguishing chiller, pumps, fans, lighting and appliances electrical consumptions. So, a calculation of theoretical “reference” demands and corresponding energy consumptions may help to identify over-consumptions, energy waste and potential energy savings.

Considering the number of parameters and influences which are involved in this type of calculation, it seems more rational to use a simulation model rather than a hypothetical weather index as heating/cooling degree-days (André et al., 2006a). For this targeted work, simulation tools are required to be easy-to-use, transparent, reliable, accurate enough and robust.

The simulation tool presented hereunder includes a mono-zone dynamic building model and a static HVAC system model. The first part of the model simulates the thermal behaviour of a whole commercial building and ensures the calculation of heating and cooling loads. The second part involves moving from building demands to system energy consumptions. The whole model is implemented in an Engineering Equation Solver (Klein et al., 2002).

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2. CONTRIBUTION TO AUDIT

When starting an audit procedure, the auditor has to collect some information about the building and the related HVAC system to be audited (building fabric, HVAC system, monthly energy consumptions,…). Using only this global data, the auditor cannot describe what constitutes “good”, “average” and “bad” energy performance with accuracy. Some theoretical reference performances (or benchmarks) have to be established to allow analysis and interpretation of the current performances of the building.

Hourly and sub-hourly simulations are very useful when having to estimate energy consumption and the performances of a given Building-HVAC system.

The simulation tool must include realistic and practical considerations as :
- building (static and dynamic) behaviour,
- weather and occupancy loads,
- comfort requirements and control strategies (air quality, air temperature and humidity),
- full air conditioning process actually performed,
- characteristics of all HVAC system components (terminal units, Air Handling Units, air and water distribution, plants)

The level of detail required for the calculation of the demands can vary a lot from case to case. For heating calculations, the major issues are a correct description of the building envelope and an accurate evaluation of air renewal. For cooling calculations, the fenestration
area and orientation, the intensity and distribution of internal gains, the ventilation rates and
the geographical location appear as critical issues (André et al., 2006a).

Furthermore, the simulation model is also required to be usable with a limited quantity of
information only. To this end, the amount of parameters to introduce in the model is reduced
to a minimum. These parameters mainly consist in the dimensions of the building, the
approximate characteristics of the envelope, the type of HVAC system components and the
main control strategies. The use of a simplified and robust model, considering the building as
a unique volume surrounded by its envelope and including HVAC equipments, is consistent
with the aim and the topic of the audit procedure: analysing the demands of the building and
identifying critical issues.

The simulation results are easy to compare to the current performances and consumptions of
the building. This comparison allows us to identify the main energy consumers in the
building, the possible discomfort and the energy saving potentials.

The present simulation tool is not adapted to highlight potential simultaneity in the
Heating/Cooling demands and some very specific retrofit opportunities, as condenser heat
recovery or reversible heat pumping potential. Other specific models are being developed by
Lebrun et al. in the frame of the IEA-ECBCS Annex48 project (2007a and 2007b). However,
as shown hereunder, a large range of basic HVAC systems are already included in the present
benchmarking tool.

3. MODELLING

As already mentioned, the global model presented here includes a building model and a
HVAC system model. These two models are submitted to different loads and interact at each
time step with a control module (Figure 1).

![Model block diagram](image)

Figure 1: Model block diagram

The main phenomena involved in building dynamics are considered to compute realistic
heating and cooling demands. Indeed, the indoor conditions of the zone comes from the
equilibrium established between an important number of influences (Figure 2). A compromise
is made between the number of the 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 taken into account. At the moment, other influences as thermal bridges and
hygroscopy of the walls are not included.
3.1. Building Model

The mono-zone building model is based on a simplified equivalent R-C network including five thermal masses (Figure 3), corresponding to a large occupancy zone, surrounded by external glazed and opaque walls. This scheme corresponds to a typical office building, mainly composed of lattice structure and slabs.

Massive opaque walls are simulated using classical 1st order R-C “two-port networks”. A 2RC module is associated to each massive wall. The wall network corresponds either to imposed temperature boundary conditions (for ‘external’ massive walls in contact with outdoor conditions) or to null heat flow boundary conditions (for ceiling and floor slabs separating two heated zones).

The fifth capacity ($C_{in}$) corresponds to the global thermal mass of indoor air and furniture (Figure 3).

The parameters of each “two-port network” are adjusted through a frequency characteristic analysis based on the computation of the zone admittance matrix (Masy, 2006). In the case of an “adiabatic wall”, the two-port network can be reduced to a simple branch composed of one resistance and one capacity.
As proposed by Laustsen et al. (2006), the actual solar factor at each time step is defined as a function of the normal solar factor and the solar incidence angle (Figure 5). Solar gains entering the zone are distributed over all internal surfaces surrounding the zone.

As shown in Figure 3, ventilation and infiltration flow rates are directly injected in the indoor node. Sensible heat/cool generated by terminal units and sensible heat gains generated by occupants, lighting and appliances are also injected in the indoor node. The indoor conditions (temperature, humidity and CO₂ contamination) are computed by making a sensible, a water balance and a CO₂ balance on the indoor node.

On the outdoor side, absorbed solar radiations and emitted infrared radiations are taken into account in the heat balance made on the outdoor surface node of the external walls.

Indoor comfort indexes (PMV and PPD) are evaluated at each time step through classical Fanger’s equations (1970).

### 3.2. HVAC System Model

The system model includes most of the classical HVAC components currently available. Considering that the building model is a mono-zone model, all the equipments (AHUs, TUs, pumps,...) are gathered and modelled as “global” components. The different locations of the terminal units or of the air diffusers are not considered here.

The AHU model includes recovery system, economizer, filter, preheating coil, adiabatic humidifier, cooling coil, post heating coil, steam humidifier, main fan and return fan (Figure 6).
Of course, these components are never to be selected all together by the user in a same installation.

Originally, three types of component models are developed (André et al., 2006b):
- complete, validated, detailed and accurate reference models (called “mother models”), used to compute components characteristics on the basis of manufacturer data,
- simplified and robust simplified models (called “daughter models”), using previously defined characteristics to run simulations,
- simplified, robust and easy-to-tune models (called “orphan models”), directly tuned using manufacturer data.

In this “benchmarking tool”, in order to limit the number of parameters, many “default values” are proposed (mainly for components effectivenesses and pressure drops). Sizing heating and cooling powers are automatically calculated by the tool.

3.3. Control Module

Simple proportional control law is used for each component, with a non dimensional control variable $X$, varying between 0 and 1 in proportion of the difference observed between the set point and the controlled variable. The control “gain” is arbitrarily fixed as a realistic compromise between control accuracy and model robustness.

3.4. Plant Model

The “daughter” cooling plant model uses a correlation established on existing air cooled chiller to determine the COP of the machine as a function of the outdoor temperature. Part load effects are not yet taken into account.

The “daughter” heating plant model uses correlations identified by means of a classical boiler reference (“mother”) model tuned on manufacturer data (Lemort et al., 2007). The boiler efficiency is computed, at each time step, as function of the part load factor and the return water temperature (Figure 7).

The air and water distribution networks are modelled to take into account heat losses and heat gains along pipes and ducts.

![Figure 7: Boiler model curves](image)
3.5. Interface: Outputs, Inputs and Parameters of the model

The outputs, inputs and parameters are, as much as possible, selected here according to the specific needs of the auditor.

Main outputs:
- Air quality and thermal comfort requirements: CO₂ contamination, PPD and PMV
- Global power and energy consumptions: Fuel and Electricity consumptions
- HVAC components specific demands
- Performances of the mechanical equipments: COP, efficiencies,…

Main inputs:
- Weather: hourly values of temperature, humidity, global and diffuse radiations
- Nominal occupancy loads and occupancy rates
- Comfort requirements expressed by renewal rate, temperature and humidity set points.
- Control laws

Main parameters:
- Dimensions, orientation and general characteristics of the building envelope (e.g. heavy, medium or light thermal mass).
- HVAC system components actually installed in the building,
- Sizing factors of the main HVAC components

The main inputs and parameters are entered on the control panels (Figure 8). Sizing heating and cooling powers are automatically calculated and can be adjusted by the user through sizing factors. Other information as weather data and occupancy rate are provided in “lookup tables”. The main consumptions and demands are given in the “simulation results” panel. Instantaneous values of powers and temperatures can be plotted by means of the “plot function” of EES.

Figure 8: Simulation tool interface – Main window
4. EXAMPLE OF USE

An example of application of the benchmarking tool is presented hereafter. The considered typical office building has a total floor area of 15000 m², distributed over 10 floors. The technical floor, installed on the roof is not taken into account in the calculations. The building is N/S oriented and has two 50% glazed facades and two opaque facades (Figure 9). The height of the building is 30 m.

![Figure 9: Typical office building](image)

The main characteristics of the building (dimensions, orientation, geographical location, and envelope characteristics) are given in table 1.

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<td>Building height</td>
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</table>

Table 1: Characteristics of the building

Three options are imagined for this building:

1) **Original system**: Original Building + CAV system with electrical steam humidification, fan coils terminal units and without any heat recovery system,

2) **Improved HVAC**: Original system but with adiabatic humidification, air heat recovery system (cross flow exchanger),

3) **Improved Building**: Original system but insulated Building (opaque frontages U value : 0.3 W/m².K and windows U value : 2 W/m².K).
The main simulation results are presented hereafter:

**1) Original system:**
The annual energy demands are: 600 MWh of heat (~80000 m³ of natural gas), 520 MWh of cooling (~160 MWh of electricity with an average COP of 3.2) and about 1970 MWh of electricity.

The chiller electricity consumption corresponds to approximately 8% of the total electricity consumption of the building while fans, pumps, lighting and appliances are in charge of, respectively, 17%, 6%, 24% and 29% of the total electricity consumption. Electrical humidifier consumption corresponds to approximately 15% of the total consumption.

**2) 1st improvement: adding of a recovery system and replacement of humidification system**
The use of an air-air recovery system gives the following results:
290 MWh of heat (~43000 m³ of natural gas), 520 MWh of cooling (~160 MWh of electricity with an average COP of 3.2) and about 2025 MWh of electricity.

As waited the heating demand decreases. The fan electricity consumption increases slightly due to the additional pressure drop in AHU and reaches about 18% of the total electricity consumption. The distribution between the other consumers of electricity stay similar to that obtained in the first case. Electrical humidifier consumption corresponds again to approximately 15% of the total consumption.

The replacement of the electrical steam humidification system causes a decreasing of the total electricity consumption (till 1700 MWh) but also an increasing of the boiler consumption (till 598 MWh, or 82500 m³).

**3) 2nd improvement: improvement of the characteristics of the envelope**
The annual energy demands are now: 470 MWh of heat (~64000 m³ of natural gas), 620 MWh of cooling (~188 MWh of electricity with an average COP of 3.2) and about 2035 MWh of electricity.

The relative importance of the chiller electricity consumption slightly increases and reaches about 9% of the total. The distribution between the other consumers of electricity stay similar to that obtained in the first case.

As shown here above, the main energy consumers are easily highlighted by the benchmarking tool. It appears that a large part of the total electricity consumption is due to auxiliaries (fans and pumps), lighting and appliances while the part of the chiller does not exceed 10%. Steam humidification device is also an important electricity consumer and should not be neglected.

The comparison of such simulation results with the current consumptions should help identifying hidden energy waste.

At the end of the audit procedure, the tool should also be used to evaluate the main retrofit proposals identified by the auditor.
Some example of hourly results are shown in figure 10, 11 and 12.

- **Figure 10**: Outdoor (blue) and indoor (red) temperatures
- **Figure 11**: Heating (red) and Cooling demands (blue)
- **Figure 12**: Electricity power demands

5. **CONCLUSION**

The simulation tool presented here is based on one dynamic R-C building model and one static HVAC system model composed of simplified components models. Most of the parameters are automatically computed (components sizing) or fixed by default (components effectiveness) to reduce to a minimum the parameters asked to the auditor.

This benchmarking tool is developed to allow auditors to compare current and theoretical consumptions of the audited building. Because of the large amount of parameters influencing the performances of buildings and HVAC system, it should help him to identify main energy-consumers, energy waste and potential energy saving. Without simulation, the auditor would encounter a lot of difficulties in differentiating and evaluating chiller, pumps, fans, lighting and appliances electricity consumptions.

6. **REFERENCES**


7. ACKNOWLEDGMENTS

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![Intelligent Energy Europe](https://example.com)

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