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About the audit of air conditioning systems: Customer advising with the help of case studies and benchmarks, modelling and simulation

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Abstract

Article 9 of the European Building Performance Directive impose the inspection of air-conditioning plants above 12kW. Therefore, tools will be needed by the auditor or inspector. The purpose of the audit of a HVAC system is indeed to advise the customer about the energy performance of the system and to suggest modifications and improvements to be carried out. Different levels of audit are possible, ranging from a basic observation of the energy bills up to more advanced approaches involving realisation of measurement campaigns and advanced calculations. In this respect, modern simulation tools are a valuable resource that can help in improving the information gained from the audit. Such tools can be used at two levels in the context of an audit. First, upstream of the audit procedure in order to calculate the expected performance of a given system or of a family of systems. This process is called “benchmarking” as its objective is to provide reference performances for the system under investigation. This approach efficiently relies on the information gained from Case Studies. Then, simulation can be used during the audit procedure in order to complement the information obtained from observation or measurements and to extrapolate the performance of the system and, more important, the change of performance which could be obtained by submitting the system to some modifications (in the design and/or in the operation).

This paper outlines such an approach as developed inside the AUDITAC project (funded by the European Union under the “Intelligent Energy for Europe” program). It addresses the different aspects of the analysis: selection of case studies and use of information obtained from this analysis; calculation of benchmarks including presentation of the different simulation models used in that context; integration of those elements in an advising method or tool devoted to the information of the customer. This customer advising tool is one of the deliverables of the AUDITAC project.

Introduction

The “Customer Advising Tool” is one of the main deliverables of the AuditAC project. It is based upon the lessons obtained from a selection of Case Studies and on benchmark performances calculated by simulation models. This tool is devoted to the audit and inspection of A/C systems, from the viewpoint of both the customer or the inspector. It is a tool that is considered of great importance to make the auditing procedure more efficient and able to produce results in line with the requirements of the

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European Building Performance Directive. This paper presents the current status of this deliverable of of the AUDITAC project as well as that of its different components. .

The paper will focus on the method proposed to produce the benchmarks and on the different simulation models that are required in the benchmarking operation. The relations between the benchmarking operation, the case studies and the advising tool are highlighted in the paper.

General presentation of the Customer Advising Tool

The (ambitious) objective of the audit of a HVAC system is to advise the customer: the auditor has to tell the customer what might be done, and for what cost, in order to improve the energy performance of an existing HVAC system.

The AUDITAC project hopes to bring this dream much closer to reality, through some practical tools developed in the European "AUDITAC" project. These tools include:

- A Case Studies centred database
- An advising method, and
- A set of performance benchmarks.

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The focus of AUDITAC is on the use of air conditioning in *cooling* mode only. Heating is not addressed in this project.

In deciding the form that the AUDITAC advice should take, consideration was given to the very first question that an audit or inspection should answer, which is 'Is the building under consideration in need of an audit?' One of the main aims of the AUDITAC project is to produce information in the appropriate form to answer this question quickly and efficiently.

A positive answer could be arrived at if the following facts apply to the A/C system and/or building under consideration:

- The HVAC is not providing correct control of indoor air quality (IAQ), indoor temperature and/or indoor air humidity.
- The running costs and/or the environmental impacts are excessive or unacceptable in terms of peak power, energy and fluid consumptions, maintenance and reparation costs, environmental impact, safety, etc

The advising tool under development by the AUDITAC project will synthesise the best aspects of the various current or proposed A/C inspection methodologies in Europe. The aim is to produce a tool which will lead the user through a methodology tailored to meet the situation they face in a particular building.

The heart of this tool is proposed to be the database, which contains Case Studies of real actions undertaken in real systems, and the savings that were obtained. The database also contains the results and findings from modelling exercises undertaken on the various system types, right down to component level.

Using the tool to tailor the methodology to the actual system to be inspected/audited, will enable both building/system owners and experienced inspectors to, amongst other things:

- Identify the A/C system types they have installed in their buildings
- Identify the specific equipment installed, through linking into the information available from Eurovent
- Identify whether the A/C systems installed meet typical benchmarks for that type of system.

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- Identify whether the system as installed appears to have room for improvement, and where that improvement might be made.
- Identify the common defects to be found for the identified A/C system type, typical remedies, and the typical energy and cost savings to be made from rectifying the defects.
- Identify real world Case Studies which have achieved energy savings in systems and buildings related to the situation being audited.

The tool is intended to be designed to minimise the time taken to appraise a specific situation by removing all guidance which is superfluous for that situation, and by then leading the user through a methodology designed to provide as much useful information as quickly as possible.

It is anticipated that the tool will be both web-based and downloadable, to enable it to be run as a stand-alone programme on a laptop while on site.

With respect to the available and on-going developments which are taking place in the field of audit, this particular approach intends to bring the latest developments of building and HVAC simulation at the benefit of the auditor. So much progress was indeed performed in the last years to make modern and efficient simulation tools reliable and easier to use in a design or operation context that it would be a pity not to transpose this body of knowledge in the audit field. For instance, efficient use of building and HVAC simulation allows to better identify the terms of the energy balance of a building or of a system in this building. It can also be used to predict, with an increasing level of accuracy, the consequences of a given choice: replacement of a component, modification to the control strategy,…

The Case Studies database

Answering the question of the need of an audit and also going further in the audit procedure requires some strong references. Case Studies will help a lot if they are made reliable; to this end the documentation of each Case Study must contain sufficient information to allow the user to transpose it to their specific problem (specific building, specific climate, specific occupancy, specific requirements and specific HVAC system).

Simulation models are a vital part of the methodology behind the Customer Advising Tool. In fact, there is always some (implicit or explicit) simulation behind any of these “transpositions” and “adaptations”. For example, assuming that some energy performance improvement can be transposed from one to another case is, de facto, a (basic) simulation.

To enable an appraisal of how a system might be improved requires entering some details of the (sensible and latent) cooling demands and of the air conditioning process actually used.
However, to make this part of a general methodology requires great care as there are, along this way, a lot of traps:

- There is no simple relationship between the cooling demand and the climate;
- Actual building occupancy is never well defined and it has a big impact on the cooling demand;
- The majority of so-called “air conditioning” systems are actually not able to achieve all the three air conditioning requirements (IAQ, indoor temperature and indoor humidity);
- A large percentage of existing air conditioning systems were never correctly balanced,or commissioned, and are rarely well maintained;
- In many cases as well, the full control and management potentials were never used and no optimisation has ever been performed;
- Users requirements and complaints are poorly, or never, recorded. So it is difficult to assess what the potential problems might be from a time limited survey.

The last point (uncertainty about requirements and complaints) adds greatly to the complexity of the advice to be provided. How are we to compare the energy consumptions of two systems, if they are not achieving the same comfort level? How is it possible to convert a violation of comfort requirement in “equivalent” energy terms?

Figure 1 shows the general approach which is proposed for the use of case studies in the Customer Advice context.

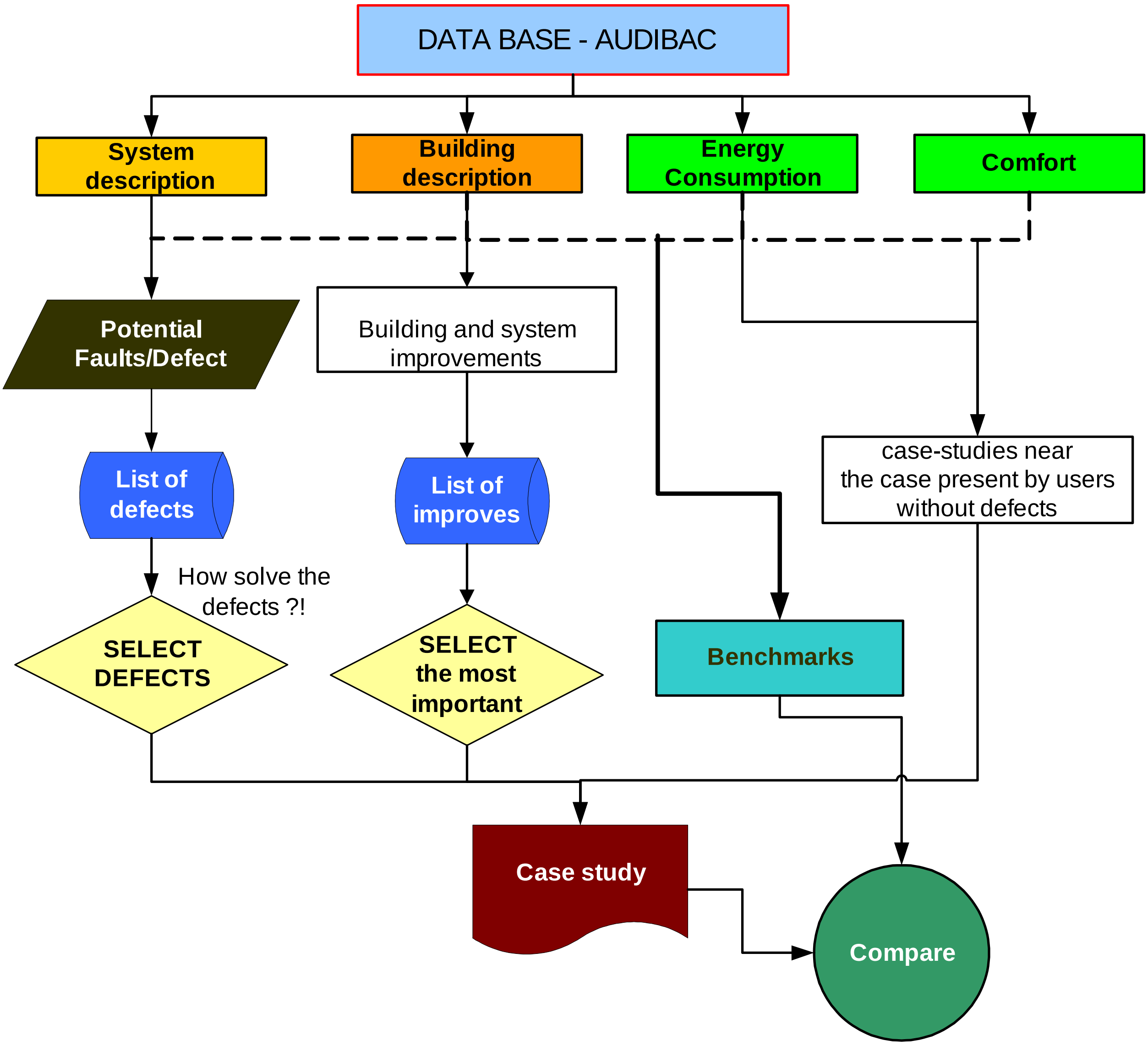

Fig. 1: How to use the case studies database in a Customer Advising Context.

The database contains information about the building and the associated system.Therefrom, a list of potential defects and improvements may be identified. The database also contains information about energy performance and thermal comfort. In a typical Customer Advising process, the first step consists in finding in the database a corresponding case to which the building submitted to the audit can be compared. Different variations to the reference(ie existing) configuration can be simulated, either during the audit process or a priori for the examples populating the database.

About benchmarks

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The impossibility of describing all possible situations that might be encountered during an audit means that we have to try and find a means of describing what constitutes good, average and below average energy performance across a range of situations.
Benchmarks are therefore a vital part of the advice to be generated, but they need to be seen to be reliable and adaptable to the specific case considered.

Generation of benchmarks

When starting an audit procedure for a building, the auditor is likely to have to collect a number of items information about the building to be audited (building fabric, HVAC system, occupational regime, weather data,…).

The auditor also needs to have an idea of the energy consumption of the building (including its disagreggation to a certain extent) in order to be able to compare the current performance of the building to a reliable "reference" or benchmark. Disaggregation can be achieved according to the different energy sources considered (gas, electricity,…) and/or according to the forms of energy use: heating, cooling, domestic hot water, auxiliary consumption…

Establishing benchmarked performance is not an easy task, as the energy consumption of a building can never be analysed without looking at the same time at the real services provided by energy, i.e., in the present case, occupants comfort.

When speaking about comfort, we are facing a very complex reality: this issue does not only concern *thermal,* but also *acoustic* and *visual* comfort and possibly other aspects. In so-called "thermal cooling" comfort, three basic requirements have to be fulfilled simultaneously: temperature, humidity and air quality. When auditing a building, the observed energy consumption has always to be analyzed with respect to the real (and consequently also observed) achievements of the requirements.

To establish suitable benchmarks for the range of building and A/C system types considered by the AUDITAC project, the crucial question to be answered is: what should be the range of consumption(s) for such buildings and A/C systems, in such a climates, with such occupancies, such internal loads and such actual indoor environments?

Given an audited building is not necessarly achieving a perfect comfort, the benchmarks could theoretically be obtained in two ways:

1) By calculating the consumption of reference (ideal) systems achieving the same level of (non-perfect) comfort as exists in the buildings surveyed;
2) By calculating the consumptions that a range of actual systems would have achieved if respecting their comfort requirements, and then comparing these with a calculated value for the corresponding reference systems.

The first approach is easier, but it doesn't reach the final objective: may be the system is not consuming too much, but it's still violating some of the requirements. In such case, some (comfort) retrofits would be required anyway.

Something in-between of the two approaches might be done: "bringing" the existing system to a minimum of IAQ and comfort, *before* comparing it some reference.

If comfort data are not available, establishment of benchmarks should only rely on energy performance, making the hypothesis that comfort is obtained, using therefore the following approach:

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1. Assess how A/C systems in real buildings perform from an energy viewpoint (if possible, obtain published energy consumption data for the various building and system types by European region, where this information exists).
2. Model a subset of previously monitored buildings and systems to see what their theoretical performances ought to be
3. Using the findings from this part of the work, assess how accurately the models predict the real monitored performance, and which are the main factors that affect this use. Use this accuracy range as part of the benchmark ranges to be produced,
4. Model the buildings and systems for 'ideal' performance and set this as the unachievable upper performance range
5. Find out how the real buildings and systems performed as a percentage of this ideal figure and use this information to help set benchmark ranges for good
6. Apply the modelling approach to the range of building types, systems and locations to be covered by the project to establish benchmarks for different locations and building types as well.
7. Produce a range of benchmarks for the combinations considered, and establish where the boundaries for good, average and below average A/C system energy consumption performance figures should be set as a first attempt at providing these figures. They can always be refined in the future – the main thing is to get some figures that can be used to start with.
8. As well as having looked at the holistic building and system performance figures, we also need to have assessed how individual items in A/C systems can affect the overall performance of the system, i.e. model variations in system design to assess the effects of each change on the overall system performance. The findings from this analysis go into the database to help provide guidance on actions to be taken to improve performance.

As the objective of the Auditac project is to develop a Customer Advising tool, which afterwards should be used in a typical audit procedure, the calculation of benchmarks could be carried out at two different moments: (fig.1):

During the Customer Advising Tool development and at a rather "detailed" level, taking profit of an exhaustive availability of information and data about the building, the HVAC system, the occupancy profile, the weather…
This approach is applied to the case studies analysed within the Auditac Group; it's also required to assess the validity of the proposed auditing procedure (during the development phase of the method). Using the Case Studies, the conclusions of the approach will be summarized in a dedicated Customer Advising Tool. This tool will be developed around the Database summarizing information about the different Case Studies and could be connected to a simplified simulation tool developed as part of the benchmarking phase.

During the Customer Advising Tool utilization in a typical audit procedure and therefore at a "simple" (and quick) level, using incomplete information, in the frame of a short term procedure and nevertheless ending up with reliable (and exploitable) results. It is likely that the second approach is the only one the auditor will be able (given time and resources) to put into practice. The idea here is to use a rather simplified tool with only a few parameters to input (and consequently making use of "typical" default values identified as described earlier) but still able to provide sufficiently accurate results to make decisions about the system. To assess this accuracy, comparison will be carried out by applying both levels of calculation to a set of case studies for which sufficient information is available.

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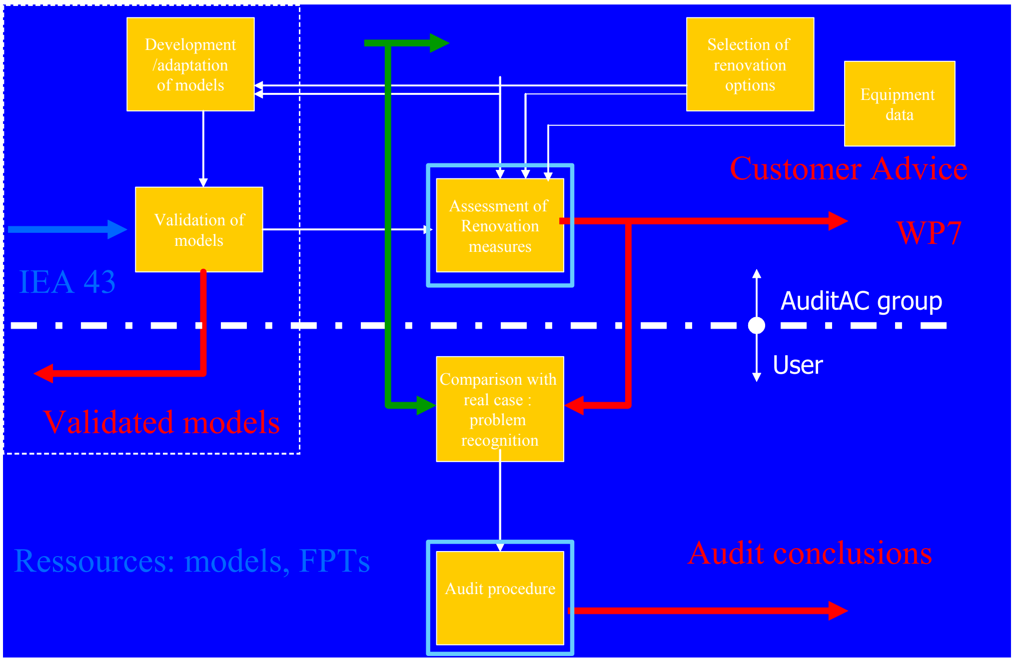

Figure 2: Connection between the two levels of analysis

Therefore, the issue of how to jump from the detailed level to the simple one is also emerging. To jump from one level to the other implies the following actions:

- population of the database: the Case Studies database should be sufficiently representative and include a variety of building types. The Customer Advising Tool should also take into account the weather dependency of the different renovation measures.

- association of the case which is the object of the audit to a sufficiently similar case in the database. In particular, the climate similarity/difference should be taken into account.

Another question which characterize the benchmarking operation is concerning the performance index which is used in order to compare the building subject to the audit and a reference case.

This performance index can be:

- The actual comfort conditions (in that case, the “reference” are the requirements);
- The building energy demand (reference = projected data);
- The Air Conditioning system energy consumption (reference = energy consumption of a comparable case)

These evaluations should ideally be carried out in sequence. Failure to fulfil the first condition makes the energy performance not representative. As mentioned above, the first “renovation” to be made in such a case is to change (estimate?), if possible, the operation of the system in order to achieve the design requirements. This could imply some additional energy use. A meaningful comparison to a benchmark energy figure can only be made under these improved conditions. This potentially implies a time lapse in the audit to allow the amended energy consumption to be assessed, but in reality the existing consumption is likely to be used to obtain an initial estimate of the energy performance of the system as it is currently operated. The audit may then identify a need for a further audit to take place at a future time to assess the true system performance.

Once the required comfort conditions are observed, then a comparison can take place between the theoretical demand of the building (A/C system?) and the measured demand. As mentioned above, end use demands are not very often directly measured in buildings.

If demands are directly measured, the interest of this comparison is to identify problems due to the building (lack of insulation, too high air renewal rate, etc…) independently of the system: for example, the building requires too much heating or cooling to maintain the comfort conditions. If measured demands for individual system components are not accessible, it is necessary to move to the next step where energy consumptions are compared. At this point, the measured consumptions are compared to the target defined in the building project.

If demands are not measured, an alternative option consists in calculating these demands using a simulation model of the building and cooling system.

Calculation of building demands

While, in an audit procedure, the field evaluation or identification of the end use of the building demand is not that straightforward (heat/cool counters are not very often installed in buildings), calculation of the theoretical demands of a building appears logically at the start of a design process as well as in an “a posteriori” evaluation procedure.

But, to calculate a “rational” cooling demand, with consideration to sensible and latent components and to corresponding temperature constraints, is a challenge. It is not simple to characterise the climate for the cooling requirements. Reference to outside dry bulb temperature and to corresponding degree-days or degree-hours does not correlate as well as for the heating demand.
Reference to wet bulb temperature or to enthalpy does not fare much better.

However, from another viewpoint, both sensible and latent cooling demands in commercial buildings are usually much less affected by building dynamics than heating, especially if the thermal mass is not accessible. A *steady state* balance model would therefore seem accurate enough in the audit context. So, rather than looking for a (very hypothetical) global weather index, similar to heating degree-days, it seems more rational to run a simulation model on a few thousands of hours, corresponding to one (or to several) cooling season(s). The current performances and capabilities of simulation tools make this approach very expedient. The climate can then be considered as it is, without any simplification.

The main simplifications are still welcome on the system (building + HVAC) side, in order to get calculation robustness, easy understanding and easy parameter identification.

The level of detail required for each calculation can be very different. For heating calculations, the major issues are a correct description of the building envelope and a reasonably accurate evaluation of the air renewal. For cooling calculations, the fenestration area and location, the level and distribution of the internal gains, the ventilation rates, the geographical location and the usability of the thermal mass (if present and accessible) appear as critical issues. Most of these issues are explicitly taken into account in current design and equipment sizing procedures.

In an audit procedure, where time and information are lacking, a more expedient method has to be carried out. For the AUDITAC project it is currently proposed that this procedure will be based on the use of “simplified” models, in which the description of the building is aggregated into a small set of parameters.

Although simplified”, the method has still to be able not only to evaluate the performance of a building as it is, but also to predict its potential performance after retrofit. Consequently, the simulation environment has to be “sensible” to those potential alterations.

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The AUDITAC project has still to decide how these models will be described.

Calculation of energy consumptions

Introducing the HVAC system involves moving from building demands to building energy consumptions. Again, the issue is to find the optimal level of detail required of the model in relationship to the amount of information which is available for the audit. Again, two levels are possible:

- A rather detailed description of the main components of the HVAC system can be considered in the development process of the audit method.
- A less detailed approach can be used in the audit realisation. Basically, the different pieces of the HVAC system can be “represented” by their respective efficiencies.

The HVAC system model has to be designed in such a way as to make clear the different efficiencies usually considered by practitioners at the levels of control, emission, distribution, and generation. Those efficiencies are very integrated quantities by nature, but should still appear as parameters or as calculated output variables in more sophisticated models. The crucial issue, in the audit context, is to find models allowing the auditor to take into account (and to be sensible to) the main renovation options that are available in the AC system. An example of such a list was published by Washington State university [ ]

Examples of Simulation Models

Here follows the presentation of some models that might be applied (although the decision has not been taken yet within the AudiAC group) in an audit procedure.

In a classical design process, the calculations are run “up-stream”, i.e. from the air conditioned zones, towards the plant, passing successively through terminal units, air and water distribution and air handling units.

Most simulation programs are organized in the same way: passing progressively from building zones to global consumptions.

But this would not be an easy way to conduct an audit: the actual demand of each zone is usually very uncertain, mainly on short time periods.

In current practice, the auditor will have to “jump” from one part of the system to another one, according to the (always very partial) information available:

The initial information usually available is split between the “extremities” of the system, namely complaints expressed by the occupants, and running costs (energy and maintenance).

Various types of very friendly simulation models of are required to assist the auditor in interpreting this sort of information.

This “friendly” character has little to do with the number of equations involved or with the calculation time required. The bottle neck is not in the computer, but in the human brain: simulation hypotheses have to be fully transparent and the number of variables and parameters has to be reduced to an absolute minimum.

Simplification is essential here, but the (design) reference models can be used to generate the simplified models which are better adapted to the audit process.

Information available in “As Built” files (design and commissioning data) should be used for initial tuning of the models.

For some of the components, careful tuning of the models would even make it possible to use them as measuring devices.

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A few examples of reference and basic models are presented hereunder and concern:

- a simplified building model compatible with an audit procedure
- a terminal unit model
- a pump and/or fan model

Very simplified building zone model

The following model is based on a very simplified steady state representation of heat and mass transfers and heat and mass balances inside the zone. It may help in checking and the measuring results.

Inside air quality (characterized by the concentration in some reference contaminant), air temperature (supposed here to be the same as globe temperature) and air moisture are the three selected output variables.

Only two parameters are here selected in order to characterise the zone: its envelope heat transfer coefficient and its "equivalent solar aperture".

Four groups of input variables are considered in order to define all the "perturbations" imposed to the zone. They concern:

The occupancy loads

The outside climate

The ventilation

The "emission(s)" of the terminal unit.

This gives the following information flow diagram:

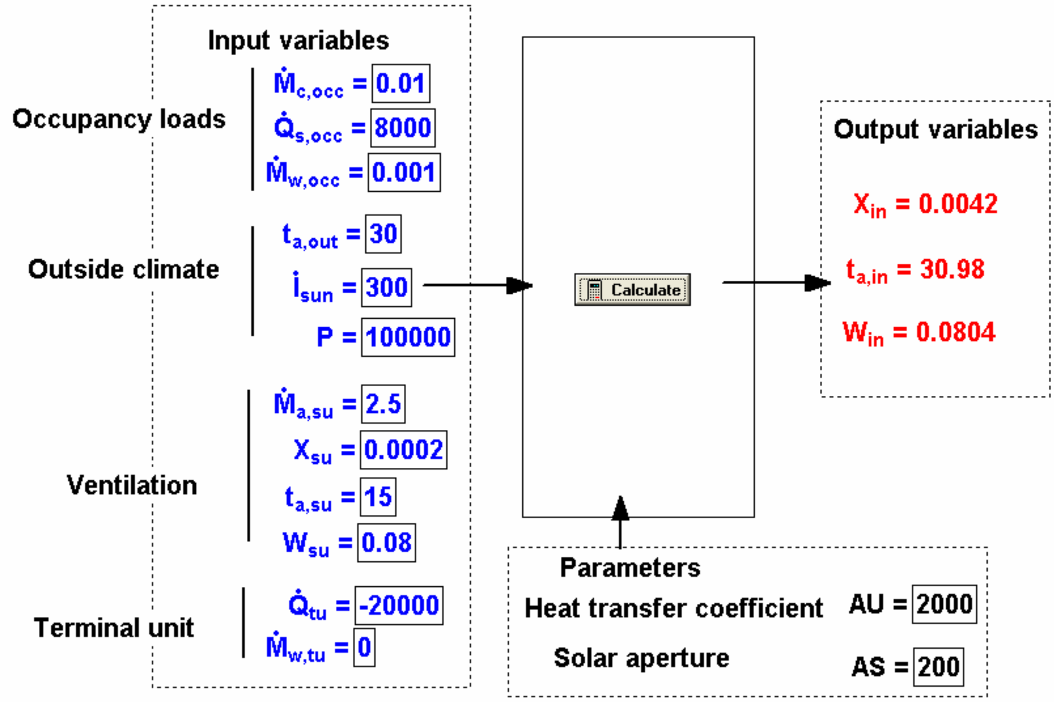

Figure 3: Block diagram of the simplified building model (EES software)

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The following equations are used:

Steady state contaminant mass balance:

$$\dot{M}_{c,occ} + \dot{M}_{a,su} \cdot (X_{su} - X_{ex}) = 0$$

Perfect mixing hypothesis:

$$X_{ex} = X_{in}$$

Steady state sensible heat balance:

$$\dot{Q}_{s,occ} + \dot{Q}_{sun} + \dot{Q}_{fabric} + \dot{Q}_{tu} + \dot{M}_{a,su} \cdot c_{p,a} \cdot (t_{a,su} - t_{a,ex}) = 0$$

$$\dot{Q}_{sun} = AS \cdot \dot{I}_{sun}$$

$$\dot{Q}_{fabric} = AU \cdot (t_{a,out} - t_{a,in})$$

$$c_{p,a} = \mathbf{Cp}\,(\text{'AirH2O'}, T = t_{a,su}, P = P, w = W_{su})$$

Perfect mixing hypothesis:

$$t_{a,ex} = t_{a,in}$$

Steady state water mass balance:

$$\dot{M}_{w,occ} + \dot{M}_{w,tu} + \dot{M}_{a,su} \cdot (W_{su} - W_{ex}) = 0$$

Perfect mixing hypothesis:

$$W_{ex} = W_{in}$$

According to specific needs, such a model is easy to complete, by introducing several adjacent zones, storage effects (in transient regime) and air transfer equation (infiltration-exfiltration in relationship with air tightness and pressure differences)…

Terminal unit used to cool a zone

The unit (for example a fan coil or a cooling ceiling system) is here considered as a semi-isothermal heat exchanger: the isothermal “fluid” is the indoor environment.

The two selected output variables are the cooling power provided to the zone and the fluid temperature at the exhaust of the unit.

The simplest approach consists in considering the unit as fully characterised by only one parameter: its heat transfer coefficient.

Three input variables have to be supplied to this model:The fluid flow rate, its supply temperature and the zone (air or globe) temperature.

This gives the following information flow diagram:

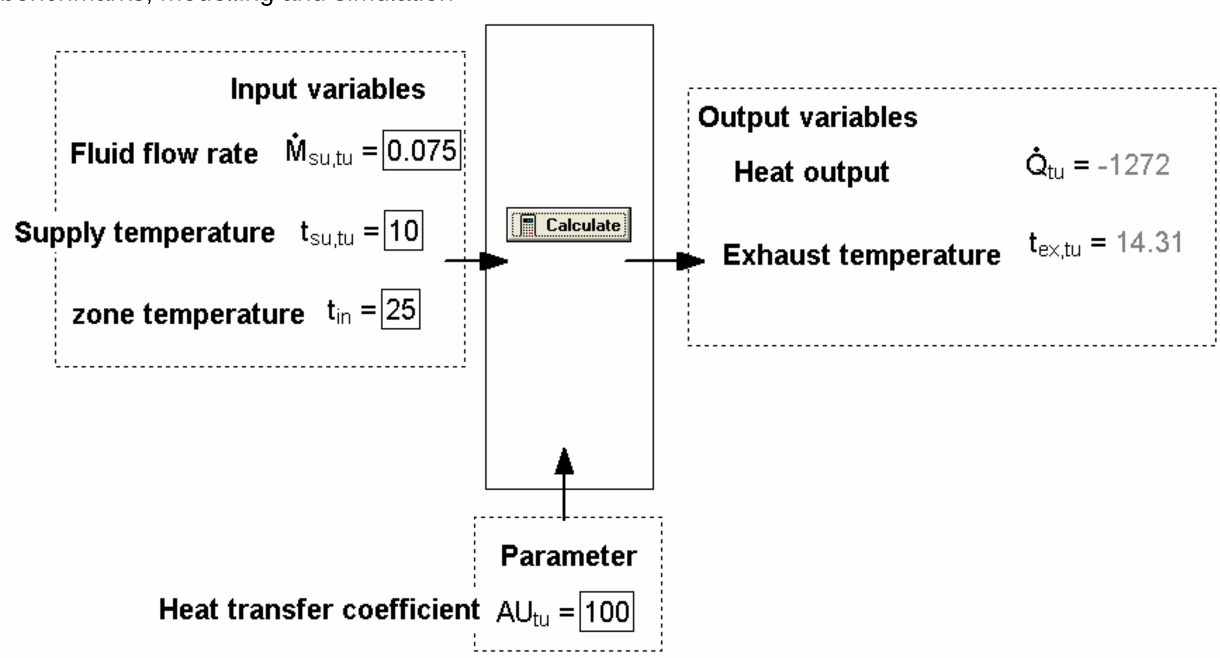

Figure 4: Block diagram of the terminal unit model (EES software)

The following equations are used:

$$\dot{Q}_{tu} = \varepsilon_{tu} \cdot \dot{C}_{tu} \cdot (t_{su,tu} - t_{in})$$

$$\varepsilon_{tu} = 1 - \mathbf{exp}(-NTU_{tu})$$

$$NTU_{tu} = \frac{AU_{tu}}{\dot{C}_{tu}}$$

$$\dot{C}_{tu} = \dot{M}_{su,tu} \cdot c_{tu}$$

$$t_{ex,tu} = t_{su,tu} - \frac{\dot{Q}_{tu}}{\dot{C}_{tu}}$$

Pumps and fans

Pumps and fans are currently modelled with the help of similarity variables: flow, pressure and power factors. These variables can be correlated to each other by polynomial expressions.

The example presented here is well fitted to the use of a variable speed fan as flow meter: the flow factor is calculated as function of the (total) pressure factor.

The main output of this model is the flow rate expressed here in “specific” value (in kg/s of *dry* air), as usually in air conditioning. Other outputs are: flow rate and pressure factors, exhaust air speed, total pressure difference, isentropic power and isentropic temperature increase across the fan (these two last outputs can be used as checking information).

The fan is supposed to be characterised by the diameter of its impeller (scale variable), the exhaust area and the coefficients of the polynomial correlation.

Supply air conditions (temperature, pressure and moisture content), rotation speed and *static* pressure difference are taken as input variables.

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This gives the following information flow diagram:

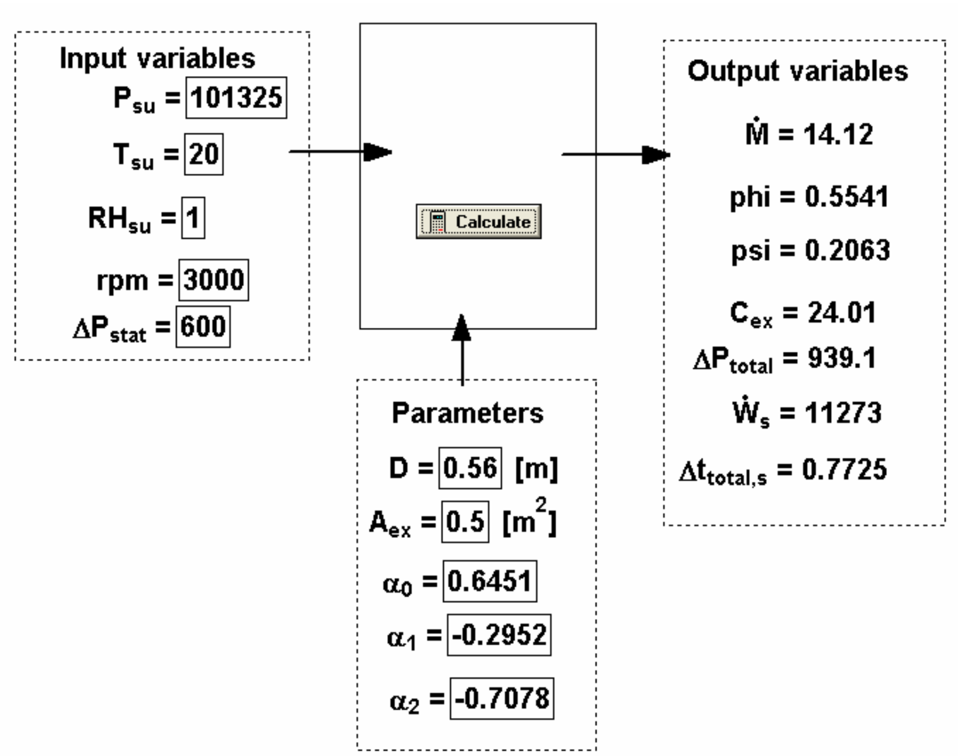

Figure 5: Block diagram of the pump/fan model (EES software)

The equations of this model are built on the basis of the definitions of two (flow and pressure) similarity factors:

$$\phi = \frac{\dot{V}}{A \cdot U}$$

Reference area:

$$A = \pi \cdot \frac{D^2}{4}$$

Peripheral speed:

$$U = \pi \cdot D \cdot N$$

rotation speed:

$$N = \frac{rpm}{60}$$

Pressure factor:

$$\psi = \frac{\Delta P_{total}}{P_{dynam,periph}}$$

$$\Delta P_{total} = \Delta P_{stat} + P_{dynam,ex}$$

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Two dynamic pressures are considered: one at the exhaust and the other one at the periphery of the impeller:

Exhaust dynamic pressure:

$$P_{dynam,ex} = \frac{c_{ex}^{2}}{2 \cdot v}$$

$$c_{ex} = \frac{\dot{V}}{A_{ex}}$$

Peripheral dynamic pressure:

$$P_{dynam,periph} = \frac{u^{2}}{2 \cdot v}$$

The following polynomial expression is used to calculate the flow factor in relationship with the pressure factor:

$$\phi = \alpha_0 + \alpha_1 \cdot \psi + \alpha_2 \cdot \psi^2$$

The following variables are then defined:

Specific mass flow rate:

$$\dot{M} = \frac{\dot{V}}{v}$$

Fan isentropic power:

$$\dot{W}_s = \dot{V} \cdot \Delta P_{total}$$

Air isentropic heating-up:

$$\Delta t_{total,s} = \frac{\dot{W}_s}{\dot{C}}$$

Air capacity flow rate:

$$\dot{C} = \dot{M} \cdot c_p$$

Conclusions

This paper has presented the current status of the customer advising tool as developed inside the Auditac project. To generate this tool, different resources are required: a case studies database in order to store, organize and allow retrieval of useful information concerning a given project; a set of benchmarks to locate the performance of the building under audit with respect to the expected performance. To calculate this expected performance, simulation tools can be used as they offer the capability of calculating the performance of a given project when submitted to some modifications and to provide, at the end, a useful information to the customer: what will be the benefit (in energy and/or financial terms) of the application of such improvements in a specific project? To provide the resources to answer such a question is one of the objective of the Auditac project.

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