TREES
Training for Renovated Energy Efficient Social housing

Section 2 Tools

2.2 Thermal simulation

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Workpackage 4 Adaptation of the material
Deliverable D3: Final version of Educational material

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Contents

1. Objectives of thermal simulation

In comparison with simplified monthly or annual calculations, dynamic simulation uses an hourly or even shorter time step, and the building model is more detailed. The advantage of this method is a better accuracy, and the possibility to evaluate the thermal comfort level of a building (or renovation) project, and not only its energy consumption. The draw back is a longer computation time, but computers have progressed so that only a few minutes are now sufficient to perform a calculation over one year.

A more detailed building model and hourly calculations allow temporal temperature variations to be accounted for (e.g. in the case of a night lowering of thermostat, and when solar gains induce overheating), as well as energy storage e.g. from noon to evening. Passive cooling techniques (solar protection, ventilation, and thermal mass) can be studied.

Renovation measures can be assessed in terms of energy saving and thermal comfort. Different measures can be compared, sensitivity studies can be performed in order to know the effect of different parameters on the building performance. Such possibilities constitute an aid during the design of a renovation project.

2. Principles and modelling

In general, a building is described as several "zones", i.e. spaces at a homogeneous temperature. Several rooms can be gathered in the same zone if their orientation is similar (e.g. north, south) as well as their use (e.g. bedrooms, living rooms). For instance north oriented bedrooms can be grouped in a single zone even if they are part of different apartments.

A heat balance is calculated in the different elements of a zone (floor, ceiling, walls…). In some models, walls are divided in smaller elements (material layers, or a layer may be divided into several elements). This heat balance can be expressed in the simple form :
gains – losses = stored energy
(these terms are defined more precisely below).

Temperature variation in the elements can be derived :
Thermal mass x temperature variation = stored energy
For the same quantity of stored energy, the temperature variation is therefore higher in a light element (low thermal mass) than in a heavy one.

Dynamic simulation tools use hourly climatic data (temperatures, solar radiation…) as an input. The output includes the heating load of each zone, and temperatures when the heating load is zero : when the heating load is positive, the temperature of a zone is the thermostat set point (or close to this value if the control is modelled with possible temporal variation) ; if solar and internal gains are higher than the heat losses, the zone temperature is higher than the thermostat set point if there is no cooling system (free floating mode).

2.1 Multi-zone model

It is usually recommended to separate north and south (or east and west) orientations in a building, except if the solar exposure is low (e.g. in a narrow street). Also, the ground floor and the last floor may have different temperatures due to heat exchanges between the roof and the (under)ground respectively. For instance the largest risk of overheating occurs in general in the last floor because of a high solar radiation received by the roof in summer. Also, the ground floor may not be constituted by apartments, so that its use may be specific (e.g. shops, storage and technical rooms etc.). The graph below shows an example of such multi-zone model.


2.2 Gains

Heat can be received by a building element due to solar radiation, « internal gains » (provided by persons, lights, domestic appliances), and the heating equipment (radiators…).

The amount of solar radiation received by the different facades is calculated hourly according to the orientation and slope of each façade, the position of the sun (azimuth, height angle), and possible distant shading (other buildings, trees…). The solar radiation transmitted by windows is also calculated according to the solar transmittance of the glazing and frame, possible architectural shading (balconies, overhangs…) and shading devices (shutters, roller blinds, Venetian blinds…).

Only a part of this incoming solar radiation is absorbed and stored in building elements, another part is reflected and sent back outside (cf. next graph).
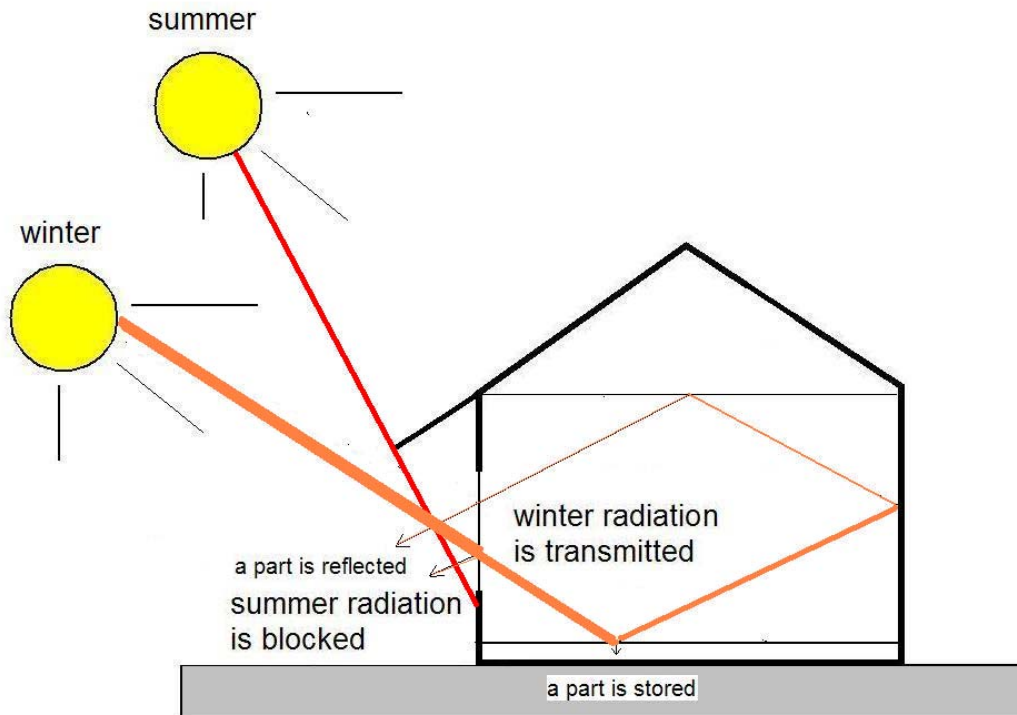
2.3 Heat losses

If it is warmer inside than outside, heat is lost through the roof, floor, walls, and windows, but also thermal bridges. A thermal bridge corresponds to an interruption of the insulation. For instance, heat can be lost through the foundation and roof edge as shown on the following graph.
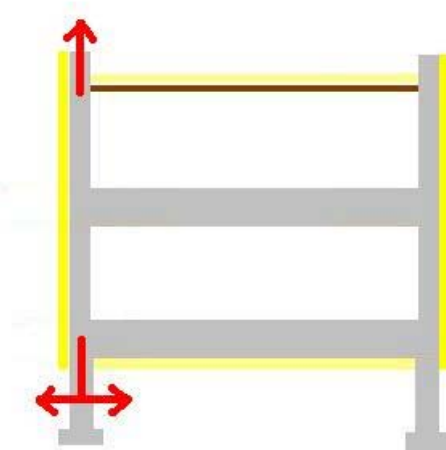
Ventilation also induces heat losses because cold air flows into the building and warm air leaves the building. Air infiltration through leakages or cracks adds an uncontrolled air flow rate, and corresponding heat losses. The following graph summarizes all heat losses.
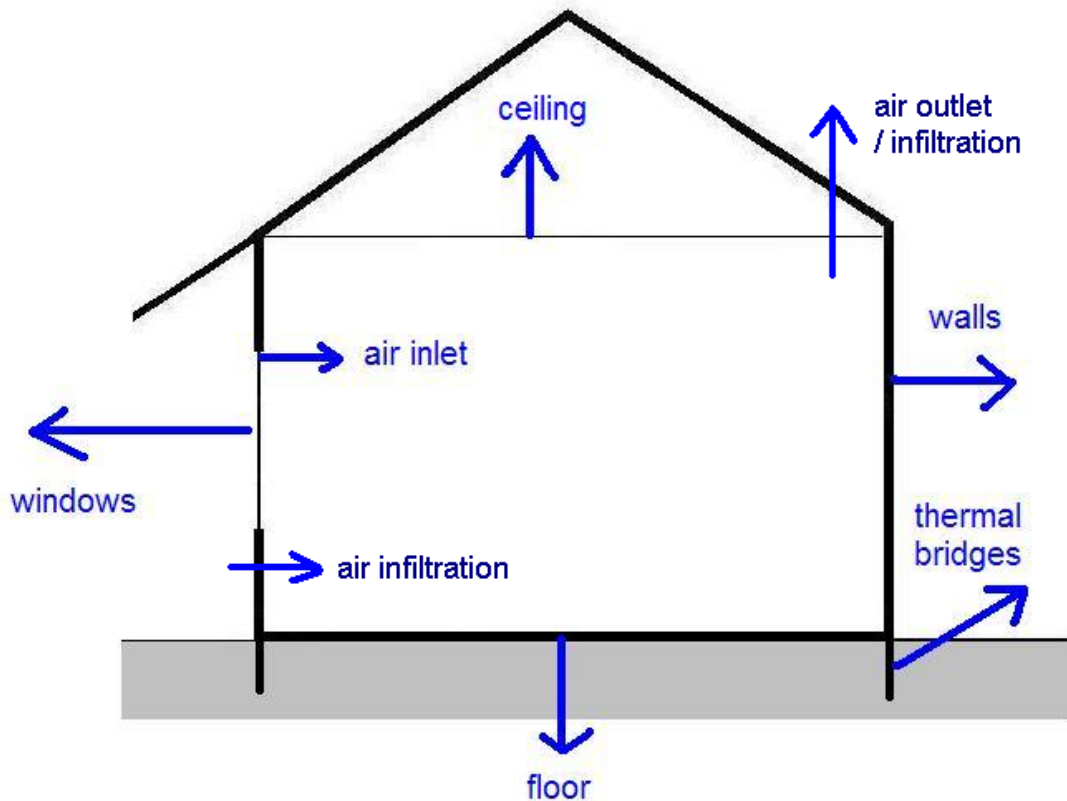
3. Use of simulation in a renovation project and main limits

Simulation can be used to evaluate the reduction of energy consumption and the improvement of thermal comfort resulting from a renovation project, to compare several alternatives and to perform sensitivity studies in order to help the designer achieving the highest performance.

The existing building has first to be modelled. Some important information is generally missing :
- sometimes, the owner does not know if the walls are insulated and this information has to be "guessed" according to the age of the building (in theory, a small hole can be made in the wall to analyse its composition, but this is rarely done in practice).
- the ventilation flow rate is difficult to assess : there may be a mechanical system, but also uncontrolled infiltration. A blower door method can be used to evaluate the air tightness of a construction but again, this is not common. If such a test is performed, the air change rate corresponding to a 50 Pa pressure difference is measured. The average air change rate for more typical pressure differences can be estimated by dividing the measured value by 20[1].
- thermal bridges may also be difficult to estimate, because detailed plans are generally not available.

These difficulties are similar when using simplified calculation tools, and they are usually solved the same way : the unknown parameters are adjusted so that the calculated energy consumption corresponds to the measured one : energy bills are generally available for several

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[1] Max Sherman, The use of blower-door data, Lawrence Berkeley Laboratory, March 1998

years, and can be averaged over 4-5 years to avoid climatic bias (some years are colder than others).

It is recommended also to measure the indoor temperature so that the calculation is performed using as realistic assumptions as possible. Standard inhabitants behaviour is generally considered for internal gains. In practice, there may be large variations between different families regarding the energy consumption corresponding to the use of domestic appliances. But this consumption generally averages if the building includes several apartments.

Knowing the characteristics of the existing building and having developed a model will allow to assess the performance of various renovation measures, e.g. implementing insulation, replacing windows etc.

Regarding comfort evaluation, possible overheating is influenced by the inhabitants behaviour : e.g. a high consumption for lighting and appliances, no proper use of solar protection and no use of night ventilation will lower the comfort level of a dwelling in summer. Again, a standard behaviour is assumed when comparing alternatives.

In some countries, thermal simulation can also be used for certification purposes : evaluating the energy consumption assuming a standard inhabitants behaviour leads to an A to G rating of the apartment or house.
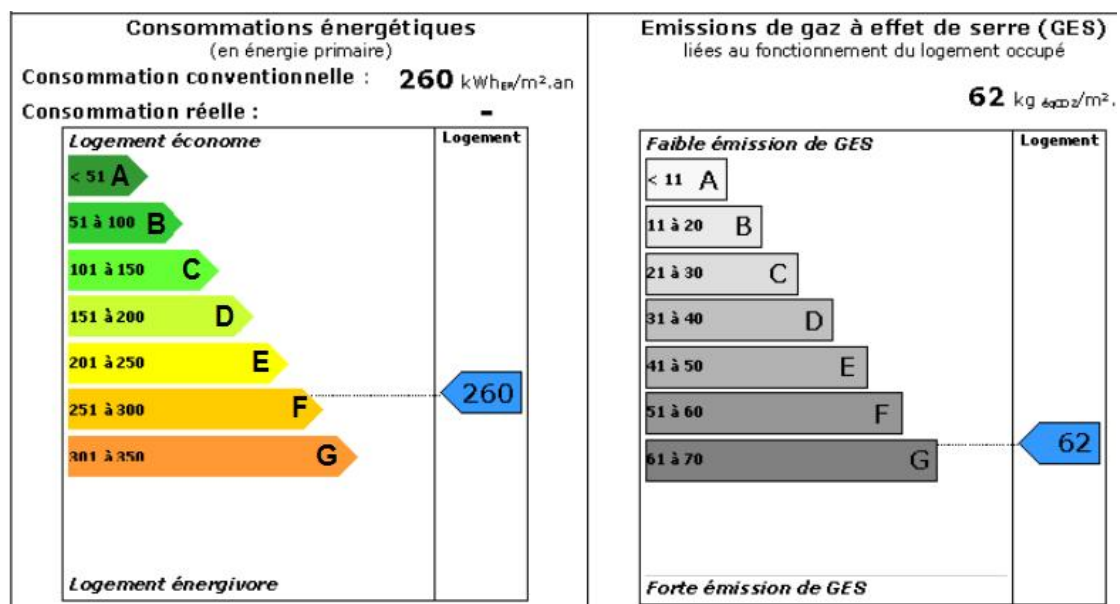
4. List of tools and web sites

A directory of thermal simulation and other building software tools has been developed by the U.S. Department of Energy : **http://www.eere.energy.gov/buildings/tools_directory/**

This directory includes around 320 software tools, listed in categories :
Whole Building Analysis
Energy Simulation
Load Calculation
Renewable Energy

Retrofit Analysis
Sustainability/Green Buildings
Codes & Standards
Materials, Components, Equipment, & Systems
Envelope Systems
HVAC Equipment and Systems
Lighting Systems
Other Applications
Atmospheric Pollution
Energy Economics
Indoor Air Quality
Multibuilding Facilities
Solar/Climate Analysis
Training
Utility Evaluation
Validation Tools
Ventilation/Airflow
Water Conservation
Misc. Applications

The directory includes a presentation form for each tool. Among the 100 building simulation tools listed in this directory, the following are more commonly used by practitioners :
ENERGY PLUS : http://www.energyplus.gov

TRNSYS : http://sel.me.wisc.edu/trnsys/downloads/download.htm

ESP-r : http://www.esru.strath.ac.uk/

TAS : http://ourworld.compuserve.com/homepages/edsl

COMFIE : www.izuba.fr

LESOCOOL : http://lesowww.epfl.ch

SIMBAD : http://ddd.cstb.fr/simbad

SUNREL : http://www.nrel.gov/buildings/sunrel/

TSBI3 : http://www.by-og-byg.dk/english/publishing/software/tsbi3e/index.htm

IDA : http://www.equa.se

5. Accuracy of models and validation

5.1 Intercode comparison

Two methods can be used to study the accuracy of a model. Experimental validation is complex in the building sector because a test building has to be constructed and monitored. Inhabited buildings are not suitable for such validation purposes because many parameters linked to the users behaviour are difficult to measure (e.g. air flow due to opening of windows and doors, internal gains due to the presence of persons and the use of appliances etc.). Test cells are therefore required, which is expensive. Monitoring and interpretation of the results is also time consuming.

Intercode comparison is simpler, allowing to study the accuracy of a tool compared to a set of models that can be considered as a reference. The example given below is a procedure

developed in the frame of International Energy Agency (IEA) activities, applied to the thermal simulation tool COMFIE.

The ANSI/ASHRAE Standard Method of Test[2] is based on the NREL/IEA BESTEST procedure[3], and specifies protocols for evaluating the technical capabilities and ranges of applicability of computer programs that calculate the thermal performance of buildings and their HVAC systems. As an example, the text hereunder presents the results of this method applied to the software COMFIE-PLEIADES 2.1 (COMFIE is a simulation tool and PLEIADES is the user interface - building description tool).

The test consists of a series of 35 building plans that progress from the extremely simple to the relatively realistic. Output values for the cases, such as annual loads, peak loads, evolution of temperatures, are compared to the predictions from 8 other building energy programs (BLAST-3.0, DOE-2.1, ESP-RV8, SERIRES/SUNCODE 5.7, SERIRES 1.2, S3PAS, TAS, TRNSYS 13.1).

The different test cases are briefly described hereunder. The base building plan is a 48 m² floor area, single storey, low mass building with rectangular-prism geometry (8m x 6m x 2.7m) and 12 m² of south-facing windows.

The sensitivity of the software is studied by varying parameters : orientation of the windows, shading devices, thermostat set point and dead band, night ventilation, thermal mass, addition of a sunspace, free-float scenario, radiative properties of walls, air infiltration, internal heat gains.
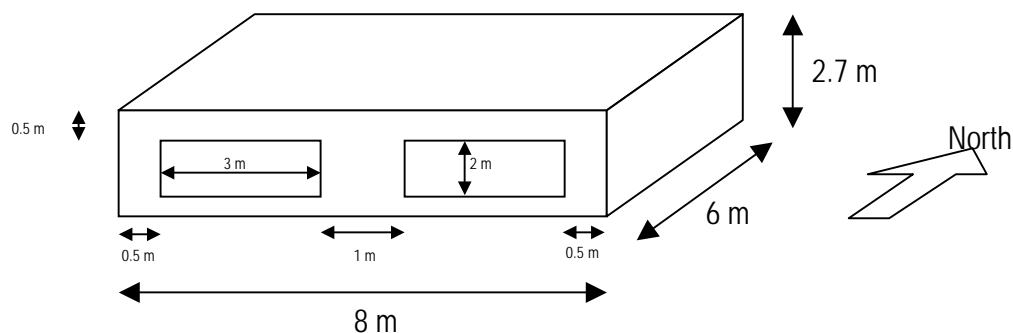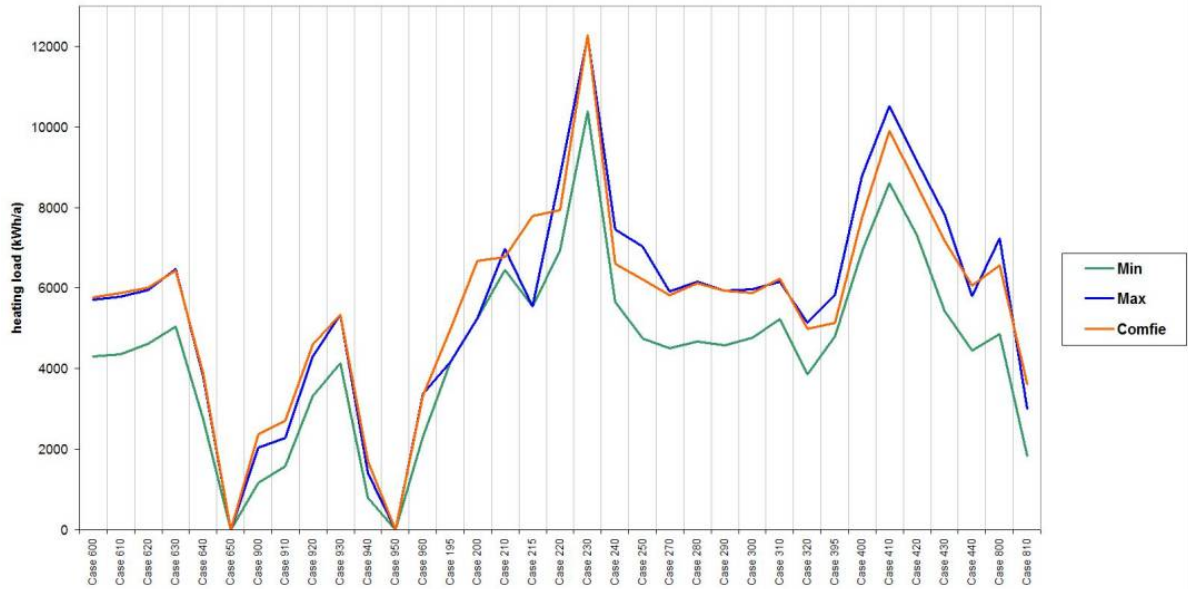

In general, the COMFIE results are near the results obtained using the other tools and the sensitivity is similar, cf. the example below concerning annual heating loads

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[2] ANSI / ASHRAE Standard 140 - 2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, ASHRAE TC 4.7, Energy calculations, 2000-2001
[3] R. Judkoff and J. Neymark, Report "International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method", NREL/TP-472-6231, National Renewable Energy Laboratory, 1617 Cole Blvd, Golden CO 80401, Feb 1995
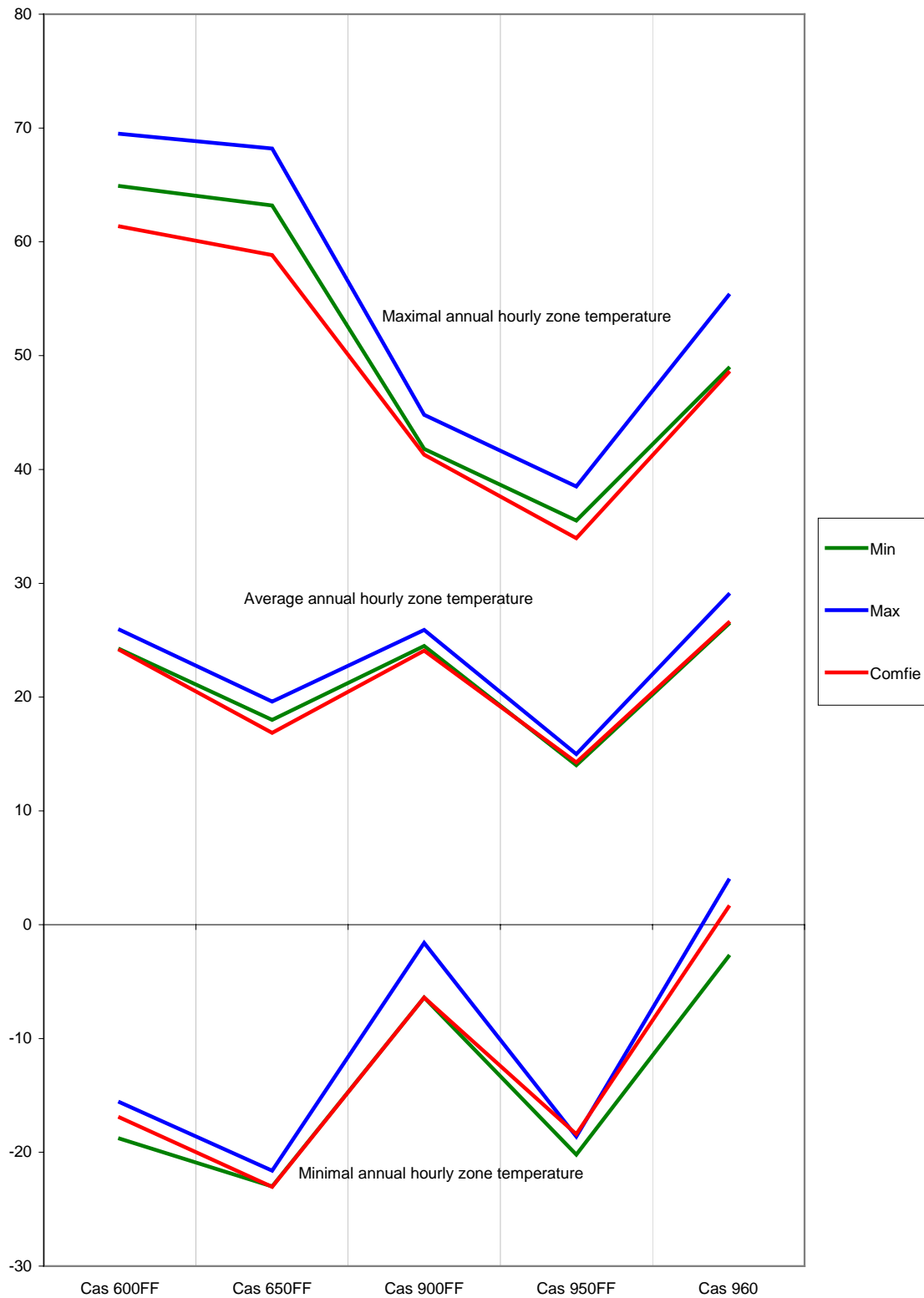
- annual heating loads

- annual cooling loads

Annual cooling loads (kWh)
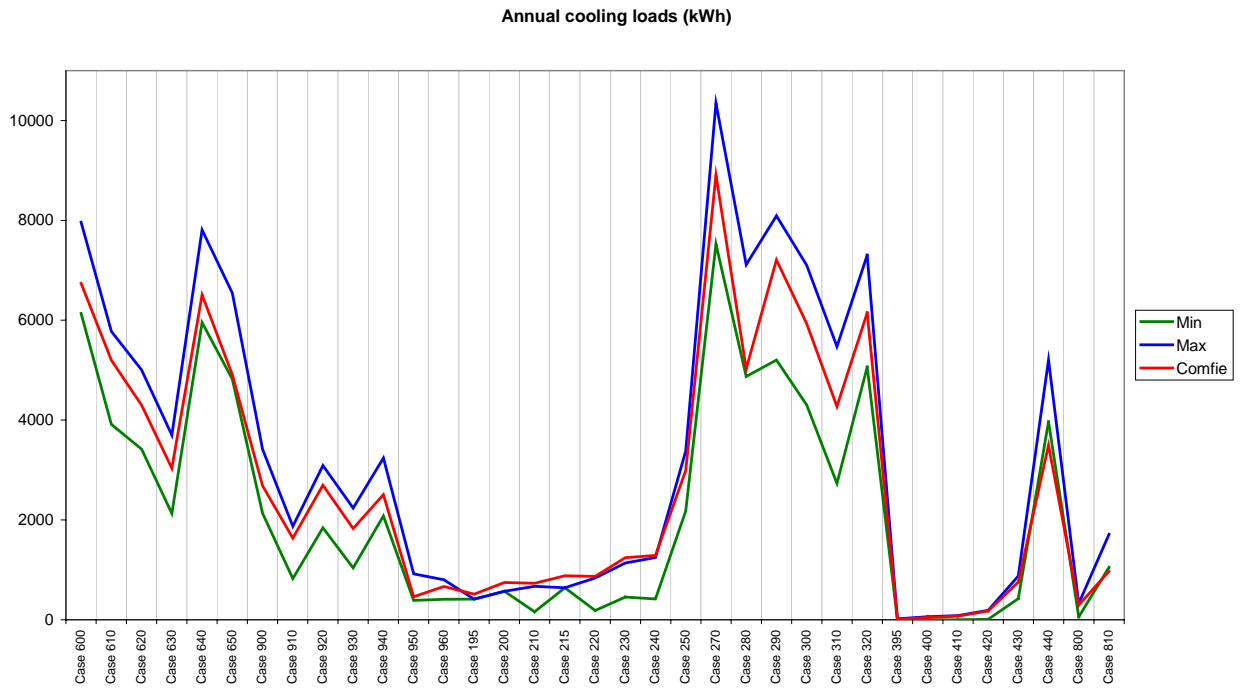
- free-float cases

Free-float maximal, minimal and average temperatures (°C)

In general, the COMFIE results are in or near the interval obtained using the other tools, the peak cooling load estimation being somewhat higher.

The relative difference between COMFIE and average results are :
Annual heating load : + 14 % (+ 2 % compared to the maximum of the example results)
Annual cooling load : + 10 % (- 12 % compared to the maximum of the example results)
Annual peak heating load : + 11 % (+ 3 % compared to the maximum of the example results)
Annual peak cooling load : + 24 % (+ 5 % compared to the maximum of the example results)

5.2 Experimental validation

In the frame of International Energy Agency activities (Solar Heating and Cooling of Buildings, task 34) simulation results have been compared to measurements in the case of a test cell built by EMPA in Dübendorf, Switzerland, see the figure hereunder.

Figure 1a Outdoor test facility with removable façade element.
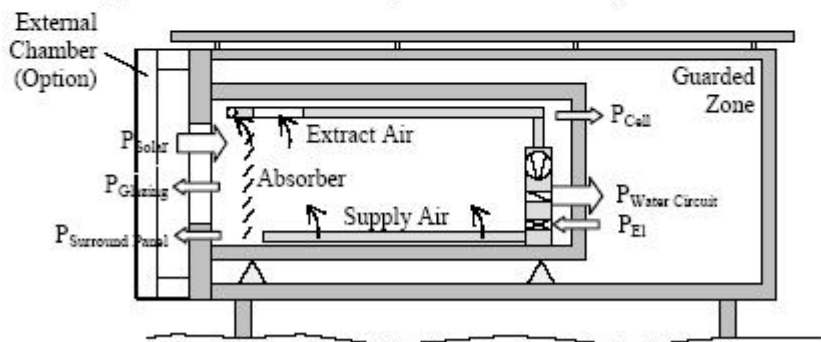
Figure 1b Diagram of test toom with an optional external chamer.
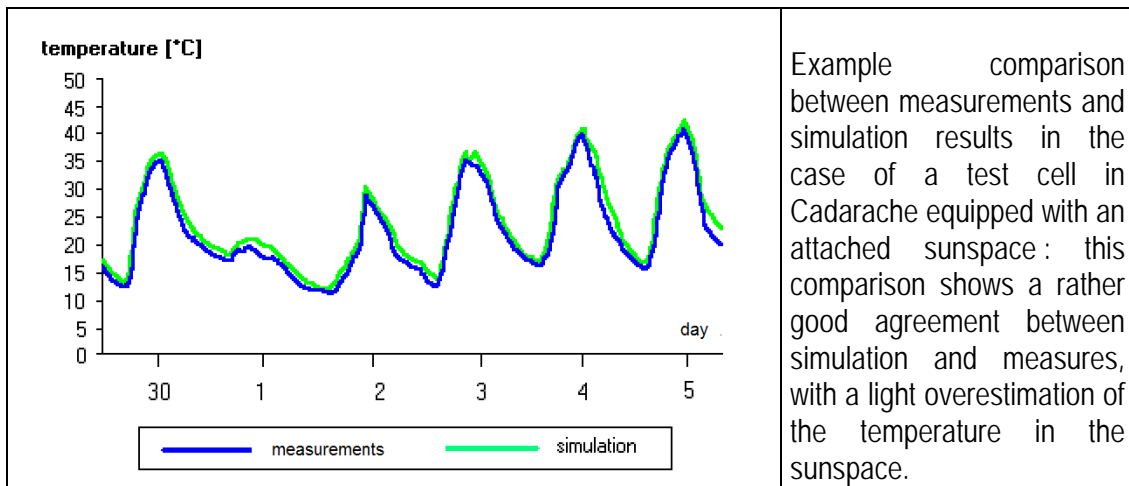
An indoor heat source has been used according to a random schedule : it was off during 55 hours, then on during 100 hours, off again 50 hours and on 5 hours, etc. The thermo-physical properties of materials and components have been measured, as well as the boundary conditions ("guarded zone"). Simulation was performed over a 600 hours period. A comparison between calculated and measured temperature profiles provides information about the accuracy of the model regarding the building dynamic behaviour, related to its thermal mass. Results using COMFIE are shown hereunder to illustrate this approach.
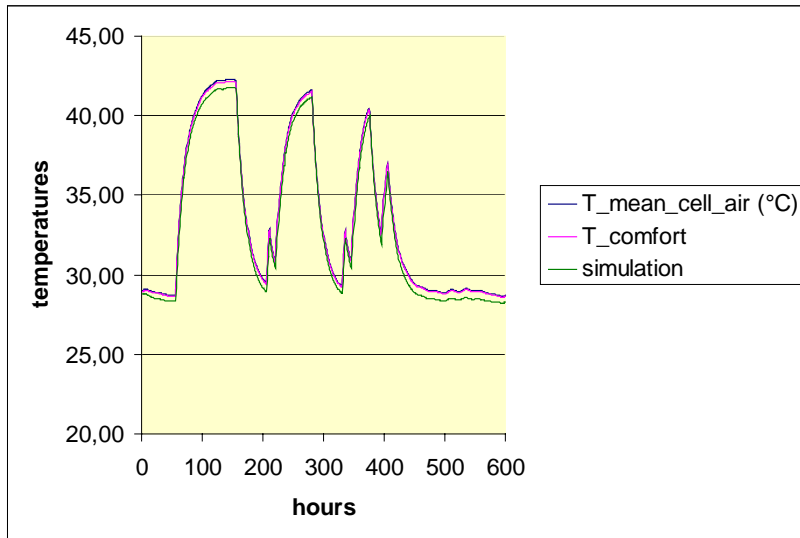
A light underestimation of temperatures can be seen : the difference Tsimulation – Tmeasured (average between air and mean radiant temperature) vary between –1,3°C and +0,2°C, the average being –0,4°C.

Among other participating tools in this study are : DOE 2 (USA), ENERGY PLUS (USA), ESP (United Kingdom), HELIOS, SIMBAD (France) and TRNSYS (USA).

The European Commission has supported in the 80's a research project, PASSYS, concerning passive solar energy. One of the activities within this project was to build test cells in different countries. These small instrumented buildings, equipped with a south façade that can be dismantled, were tested outdoor. Different types of components have been implemented on the south façade of a test cell, e.g. a standard facade including a window, a facade with an attached sunspace, transparent insulation, etc.

Example comparison between measurements and simulation results in the case of a test cell in Cadarache equipped with an attached sunspace : this comparison shows a rather good agreement between simulation and measures, with a light overestimation of the temperature in the sunspace.

6. Example simulation tool

The same simulation tool is presented hereunder as an example : COMFIE, developed by Ecole des Mines de Paris and distributed by Izuba Energies. It is based on the following steps constituting the thermal calculation module :
-   creation of a model for each thermal zone of a building,

- calculation of the irradiation data (hourly solar radiation on each surface),
- reduction of each zone model in order to reduce the computation time,
- coupling of all zone models, constituting a whole building model,
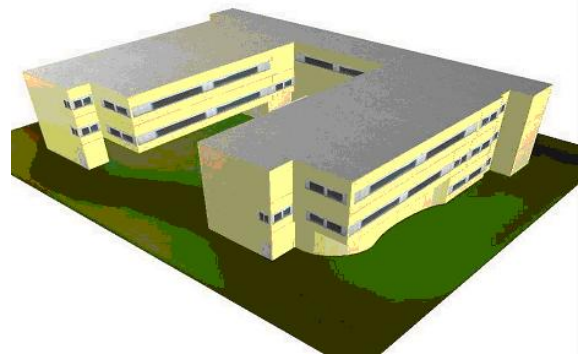- simulation with a time step between 1/10 and 1 hour.

6.1 Input

The thermal calculation module is complemented by an interface, PEIADES, and a 2-3D modeller ALCYONE, making the input and output more user friendly.

6.1.1 Geometry and main parameters

The general idea is to study a retrofit project starting from the existing building and comparing renovation alternatives. In order to make the data input easier, a user friendly interface has been developed : ALCYONE (geometry) and PLEIADES (input and output). The geometry of the building can be described using a plan as a background image and re-drawing walls, windows and doors. Re-drawing is needed because in general in any CAD system, a line could be a wall or a window or a door.
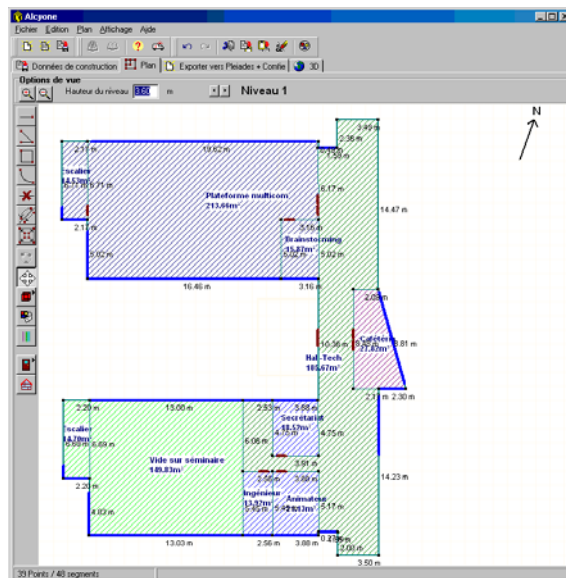

3D view, ALCYONE

2D plan imported or created using ALCYONE

The walls, floor and roof composition can be described as well as the glazing type. In a first step, the same composition is given for all external walls, other compositions for all internal walls, all floors and all ceilings, but this can be changed in a second step (e.g. the composition of the south facade may be different compared to other walls).

The wall compositions and glazing types can be chosen in a library, and the user can define specific components by giving the list of materials and thickness.
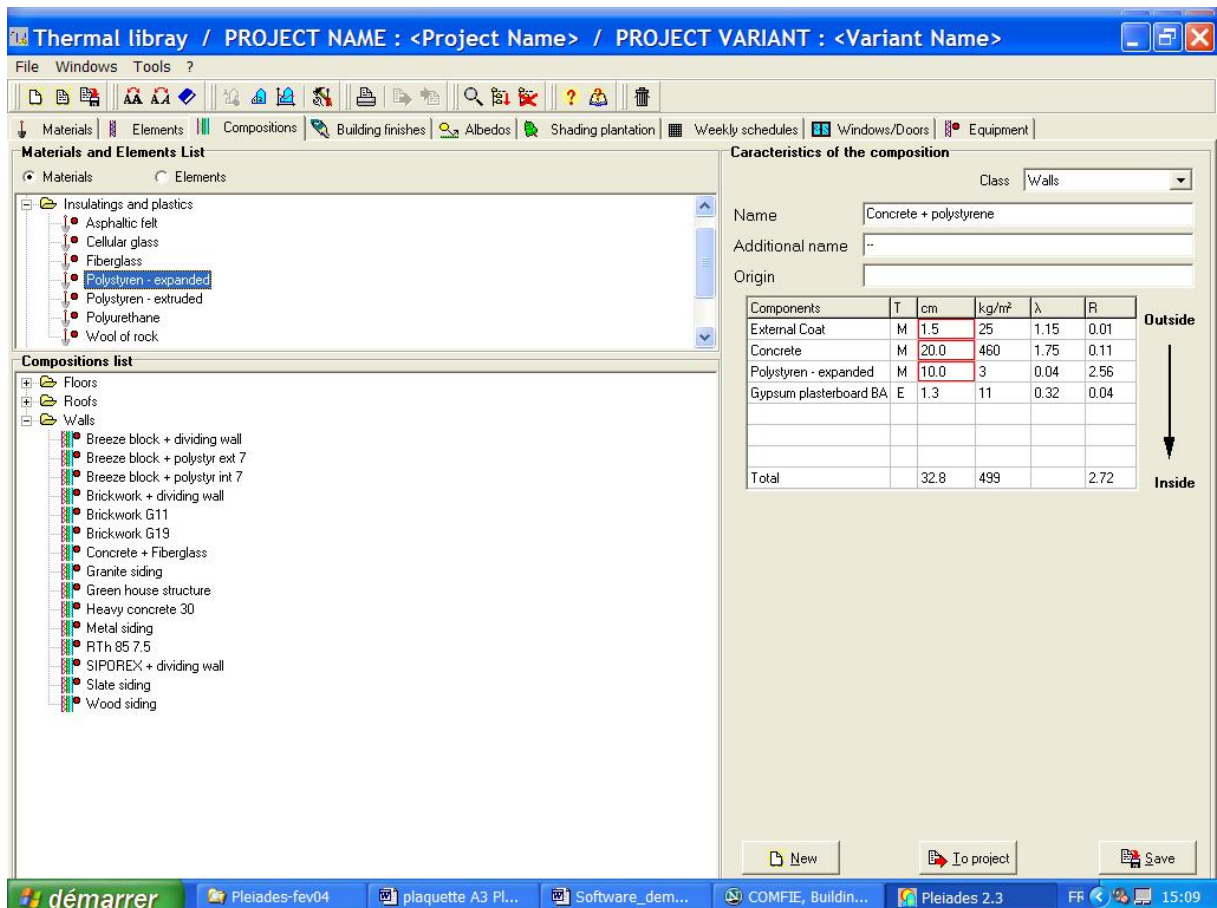
The materials can also be chosen in a library of defined by the user, the following characteristics have to be provided : density, thermal conductivity and specific heat.

The properties of windows and doors are available in a library as well or can be input by the user : heat loss coefficient U of the glass and frame, solar factor g of the glass and proportion of glass.

Some solar protection can be added in a second step (movable shading like roller blinds or shutters, vegetal shading with a monthly value of solar transmission, architectural shading like overhangs etc.).
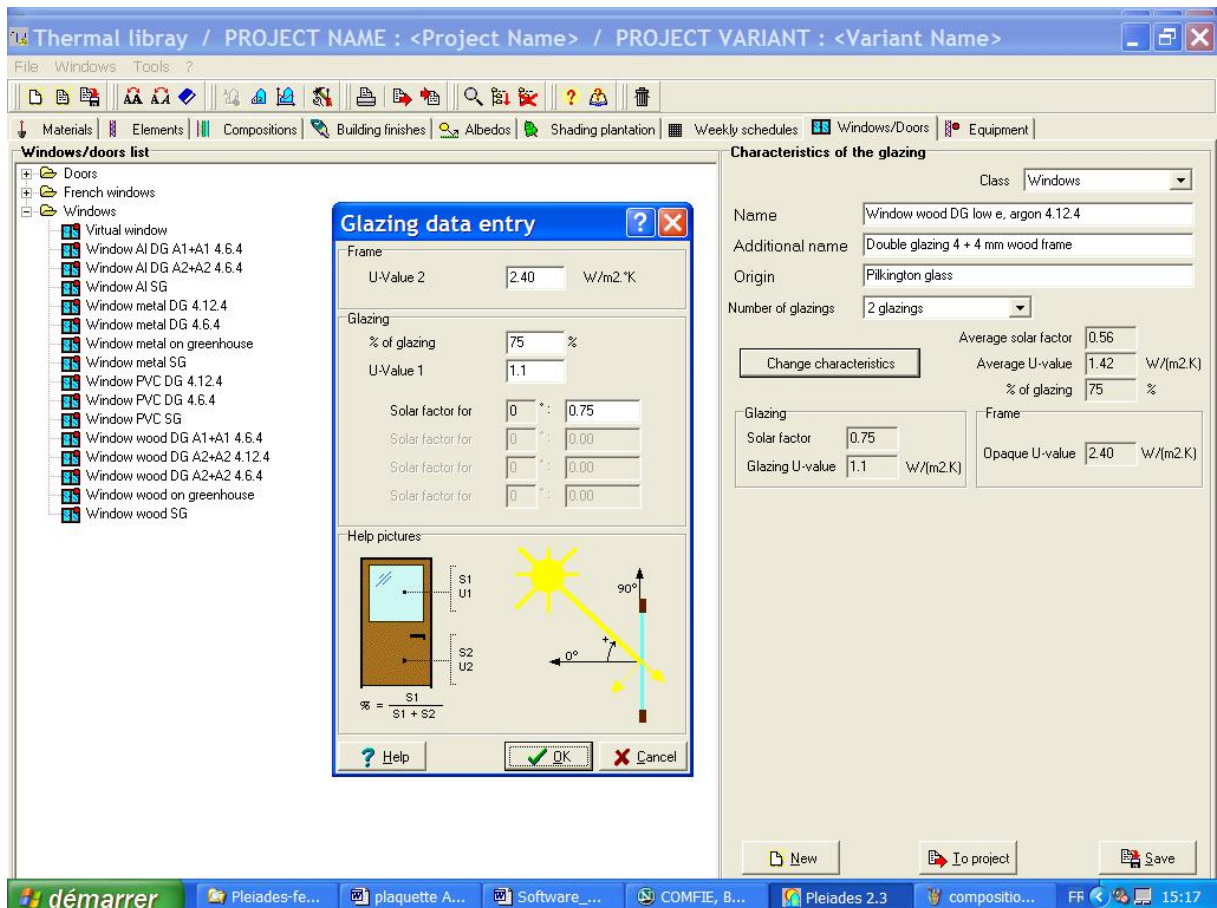
6.1.2 Other parameters

The description using ALCYONE can be refined e.g. by modifying the composition of one or several walls, the type of one or several windows, thermal bridges, adding shading devices on a window etc.

A shading element can be defined near a window, e.g. an overhang. A graph (cf. next picture) shows the monthly values of solar radiation with shading (yellow area) and without (green area). This allows different geometries to be compared in order to maximise winter gains and to minimise summer gains. The shading effect can be simulated according to the season and the hour of the day (animation, see the lower right part of the next picture).
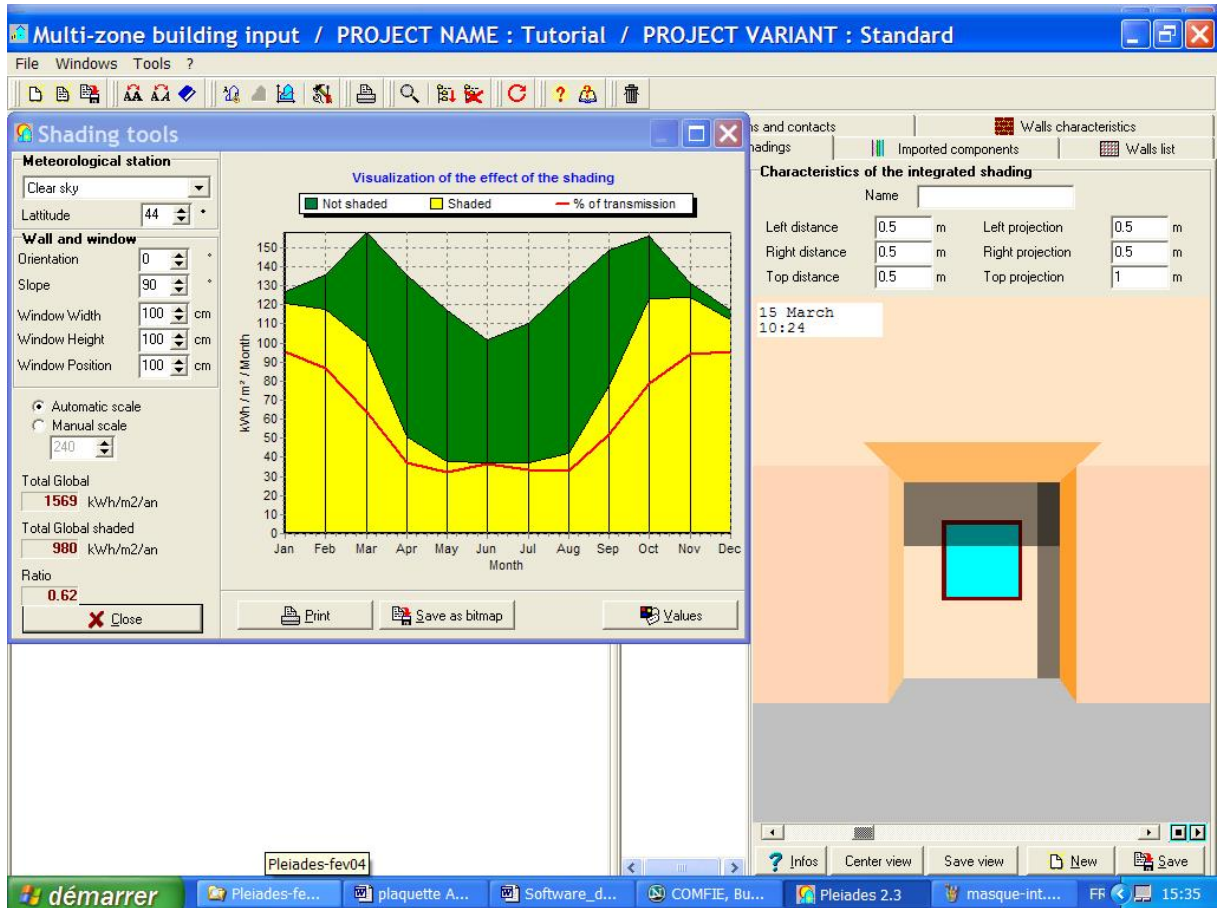
Shading from other buildings, trees, hills etc. can also be defined.
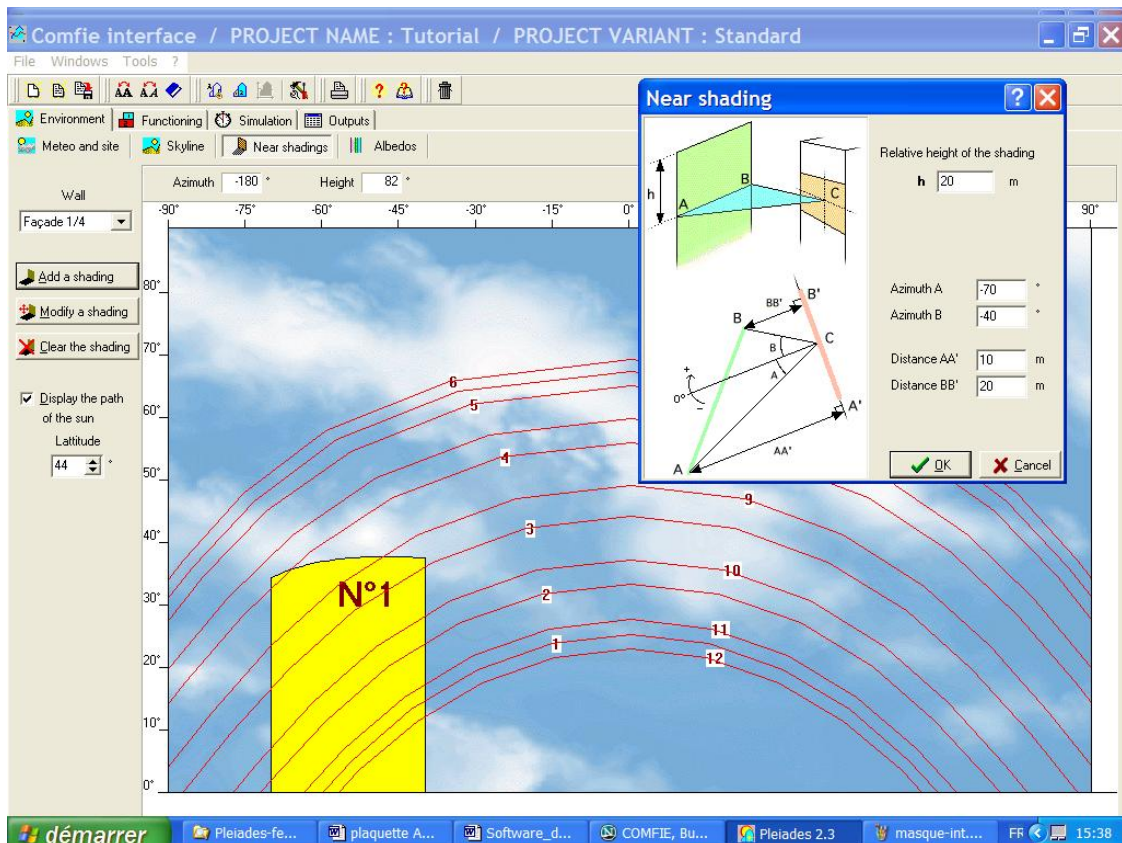
Climatic data can be chosen in a list of meteorological locations, and files can be constituted by the user including hourly values of external temperature, global and diffuse horizontal radiation during one typical year.

The use of each zone (e.g. living room, bedrooms) is characterised by different parameters that can vary each day of the week and each hour : the thermostat set point, internal gains, number of occupants, ventilation (e.g. to study passive cooling using night ventilation). Such a set of parameters constitutes a scenario that can be chosen in a library (e.g. typical dwelling) or defined by the user.

Other parameters can be defined : e.g. optical properties of surfaces, wind exposure, preheating of ventilation air, equipment and control, internal ventilation between zones etc.

The simulation time step is usually one hour to evaluate the heating demand, and ¼ h to evaluate the cooling load or thermal comfort in summer and mid season.

6.2 Output

6.2.1 Heating load and energy saving

A simulation summary table gives the heating and cooling load, minimum, mean and maximum temperature in each zone.

Different renovation measures can be compared. For instance, the following graph shows the heating load of an apartment building, expressed in kWh/m2, in terms of the insulation thickness in walls and other parameters (glazing type, ventilation).
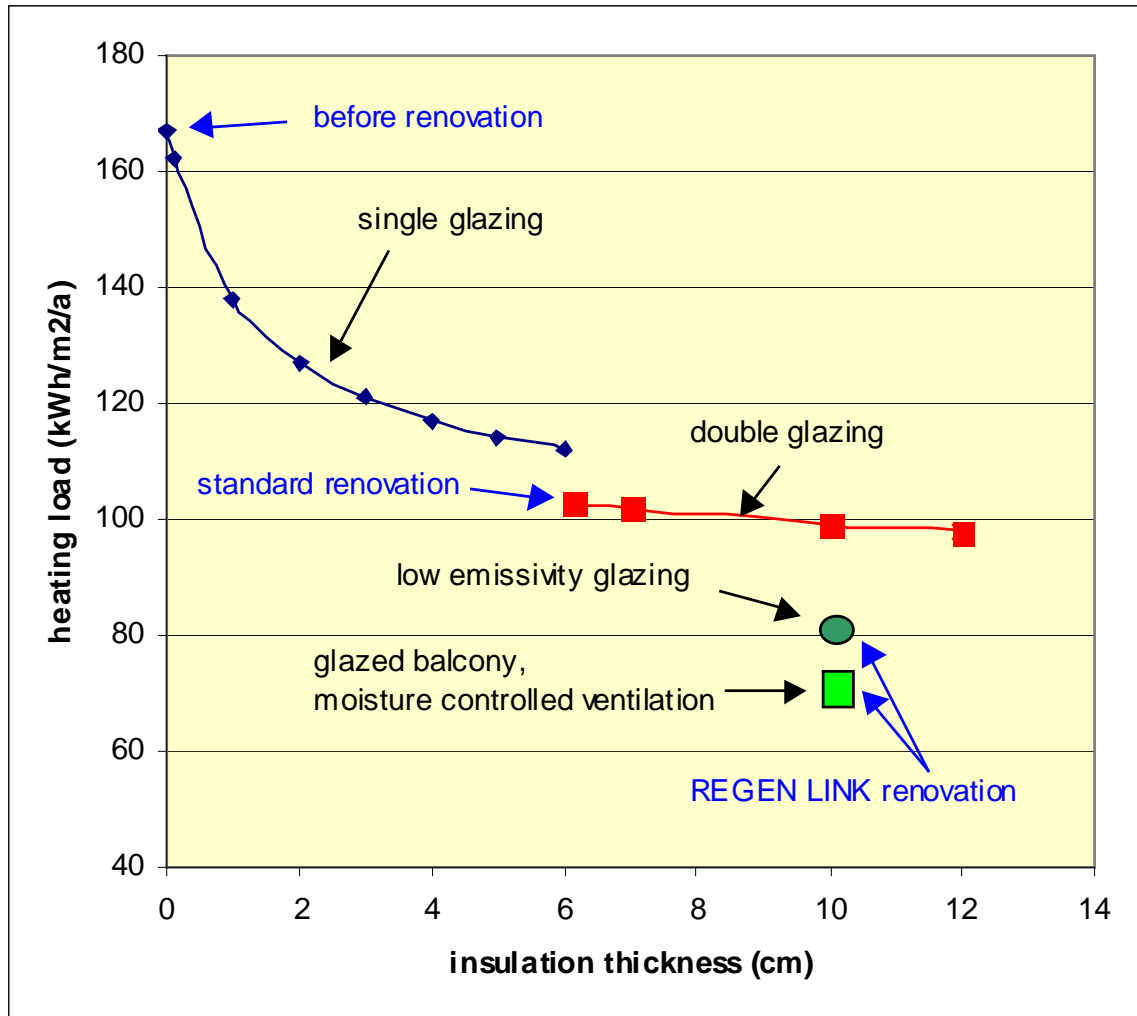

The heating load of the building before renovation is around 170 kWh/m2. Implementing 6 cm insulation on the walls and replacing single glazing by double glaing reduces this load to around 100 kWh/m2 (standard renovation). Adding 4 cm more insulation and using low emissivity glazing leads to 80 kWh/m2 heating load, which can be further reduced thanks a glazed balconies and moisture controlled ventilation ("Regen Link renovation").

6.2.2 Thermal comfort and passive cooling

Temperature profiles can be obtained by choosing a period and zones to be displayed, see next graph.
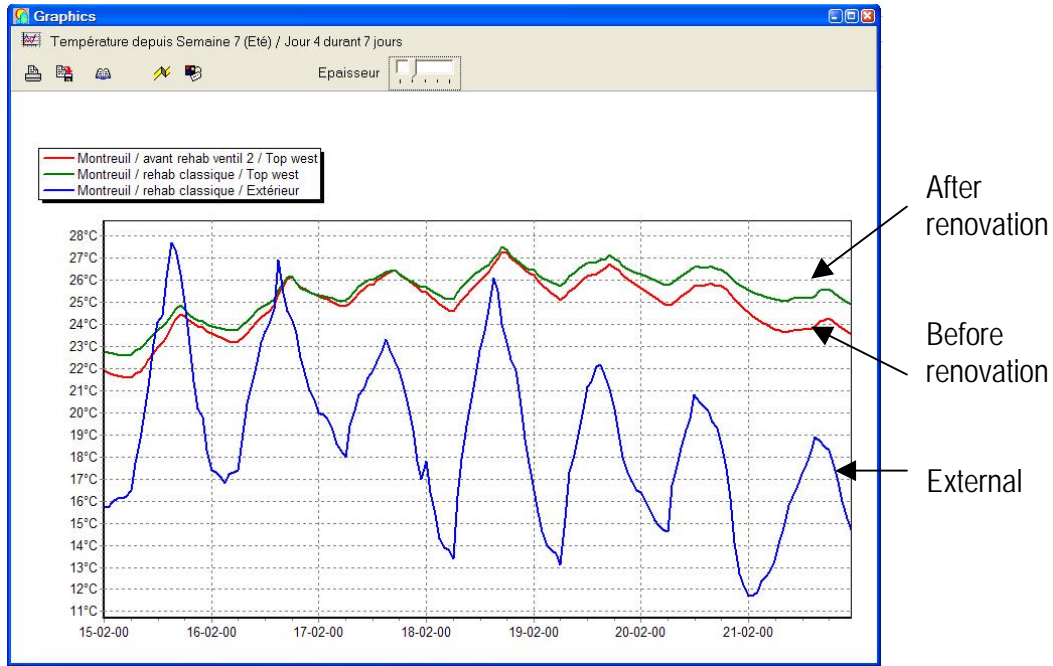
Histograms are convenient to assess globally the thermal comfort during a period : for each temperature T, such a graph shows the number of hours during which the zone temperature is T +/- 0.5°C.
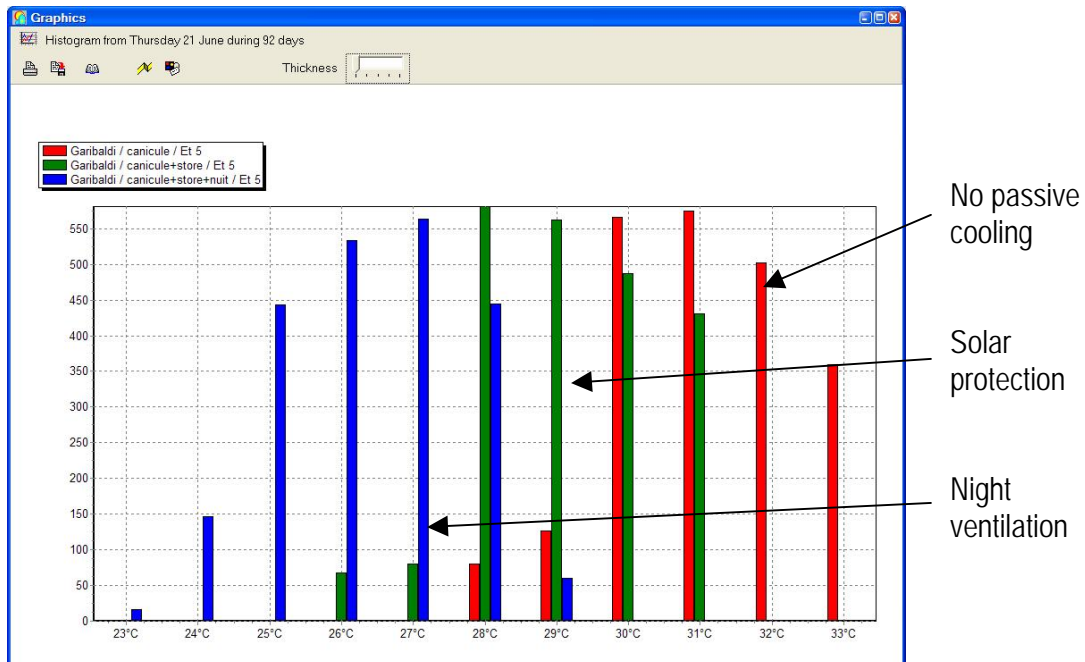
In the example graph above, the temperature rises above 30°C during around 2000 hours in a year without any passive cooling measure. The duration of the overheating period can be seen when solar protection is implemented (around 1000 hours above 30°C) and with night ventilation (temperature always lower than 30°C).

6.2.3 Sensitivity studies

Some parametric variations can be launched, e.g. choosing a composition (e.g. external wall), a material (e.g. insulation), giving the minimum thickness (e.g. 0 cm), maximum (e.g. 20) and step (e.g. 1 cm), 20 simulations are launched and the results can be compared on a graph.
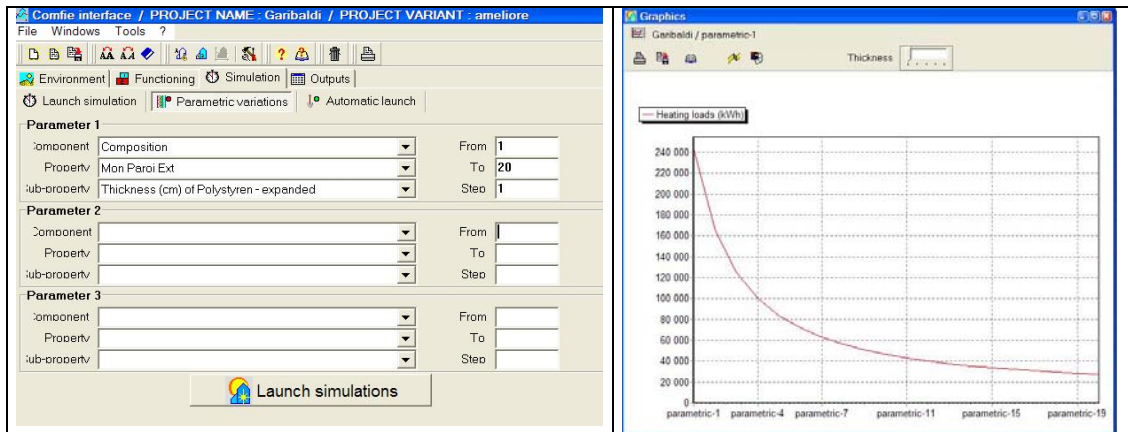
More information about the software and a free demonstration version can be downloaded from : www.izuba.fr

7. Conclusions

The main conclusions from the state of the art are the following :

▶ Thermal simulation is now widely available.

▶ It allows evaluation of energy saving and comfort.

▶ Tools are now easy to use in practice thanks to user friendly interfaces, e.g. 2D-3D graphical tools.

▶ Around 5 days are needed to study a renovation project including : modelling of the existing building, assessment of renovation measures, sensitivity studies.

▶ Thermal simulation can also be used for energy certification.