VALIDATED BUILDING SIMULATION TOOL FOR 'ACTIVE FAÇADES'

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ABSTRACT

An 'active façade' responds to (and anticipates on) changing indoor and outdoor conditions. To assess the potential of such a façade for minimising energy consumption and improving indoor comfort, a simplified building simulation model has been developed, that combines the simplicity and understanding of easy to use programs with the flexibility and possibilities of advanced programs.

To validate the program, it is applied to two ECN research facilities. The model appears to be able to adequately describe the thermal behaviour of both. In addition, its performance in this respect is comparable to that of the much more sophisticated building simulation model TRNSYS.

With the model, different strategies for sun shading, night cooling etc. can easily be assessed. The energy balance provided is a powerful aid in focussing the effort to improve the thermal performance of a dwelling. The model also allows insights into which part of the thermal mass determines indoor temperature variations.

INTRODUCTION

An 'active façade' responds to (and anticipates on) changing indoor and outdoor conditions. Sun shading devices are operated automatically, windows can be opened for night cooling using intelligent control algorithms and ventilation rates are controlled using indoor air quality sensors.

To assess the potential of an 'active façade' for minimising energy consumption and improving indoor comfort, in particular to assess the effectiveness of different control algorithms, building simulation is a powerful tool.

Pfafferott (Pfafferott, 2003) follows this approach, using a combination of an advanced building simulation model and a parametric model to assess the effect of night cooling in their office building.

Commercial building simulation programs fall into two categories:

- Simple and easy to use, but usually with limited possibilities and flexibility, in particular to model innovative concepts or components.
- Sophisticated and flexible, but complex to use and usually rather non-transparent where thermal processes are concerned.

A large variety of building simulation models is also described in the literature. Hudson (Hudson 1999) used a lumped capacitance model, that has been the basis of further simulation work, e.g. (Mendes, 2001). The development of these models tends towards higher degrees of sophistication and complexity, which makes them difficult to understand for those outside the direct environment of building simulation.

A simplified building simulation model has been developed, that combines the simplicity and understanding of easy to use programs with the flexibility and possibilities of advanced programs. It is henceforth referred to as the 'Pascal' program as it is written in the Pascal programming language. To validate the 'Pascal' program, it is applied to two of our research facilities and its output is compared to measured data. In addition, its results are compared to those of the internationally accepted and validated program TRNSYS (TRNSYS 2002).

EXPERIMENT

Experiments are carried out in two research facilities on the ECN premises. These research facilities are discussed below.

FAÇADE RESEARCH FACILITY

One of the research facilities used is specifically designed to test façades. The facility, shown in Figure 1, is of timber frame construction with artificially preserved pine panelling on the outside, and finished with gypsum boards on the inside. It consists of four 'identical' rooms that are vertically separated by a staircase extending from the front door. The rooms are thermally well insulated (U=0.15 W/m^{2}K) to minimise heat losses and minimise mutual thermal interaction. Each of the rooms holds a single active façade, two of which are shown on the right in Figure 1.

Figure 1 ECN research facility containing 4 separate rooms each holding a different façade.

The active façades, their characteristics and performances are described in detail in (Koene et al., 2005, Active façades). During the experiments discussed below, two façades were facing south (towards the right in figure 1) and the other two were facing north (towards the left in figure 1).

For ease of operation, the rooms are electrically heated, allowing accurate control of indoor temperatures and accurate monitoring of energy consumption. Temperatures of air, walls, floor etc., energy consumption as well as weather data (ambient temperature, solar irradiation and wind speed) are gathered every 10 minutes using a PC-based data-acquisition system.

Figure 2 shows the floor plan of a room with the location of sensors. Ambient temperature and wind speed are measured in a nearby weather station at a height of 10m.

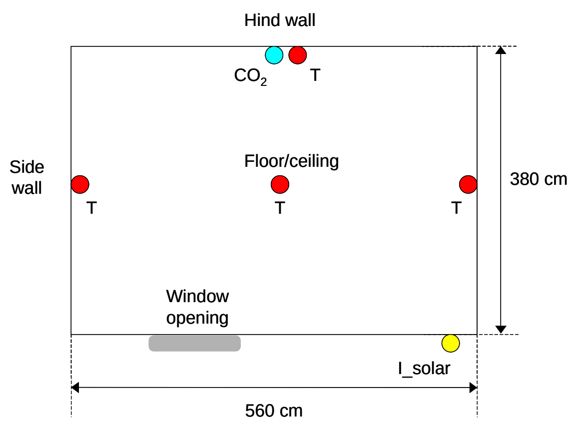

Figure 2 Floor plan of a room with the location of sensors. Sensors on the hind wall and side walls are placed at a height of 1.5m.

The computer also simulates occupation of the rooms by controlling the indoor temperature set point and controlling the dissipation of internal heat (simulating heat from occupants, lighting, appliances etc.) according to certain patterns. For night cooling, the computer automatically opens panels and windows in the façades at 11:00 p.m., allowing cool outside air to flush the rooms. At 6:00 a.m. the next day, the windows and panels are closed again. This pattern is repeated for a number of days.

In addition, CO_2 is injected in each room using a flow controller and control valves. The injection of CO_2 is not continuous as the valve to each room is opened for 100 seconds every 10 minutes. The injection point is near the middle of the room. Ventilation rates are determined from the rate of CO_2 injection and the indoor (and ambient) CO_2 concentration.

The ventilation rates thus calculated are subject to a number of uncertainties and possible errors, e.g. due to the fact that the CO_2 concentration is monitored at the hind wall rather than in the exhaust air. The whole procedure including its difficulties is discussed in detail in (Koene et al., 2005, CFD).

An example of the CO_2 concentration measured and the ventilation rate calculated is shown in figure 3 for one of the rooms for a period of 9 days in August 2004. Note that near the end of the experiment, the CO_2 concentration drops due to the draining of the CO_2-container. As a result, an erroneously high ventilation rate is calculated (which is corrected when used as input to the model, see below).

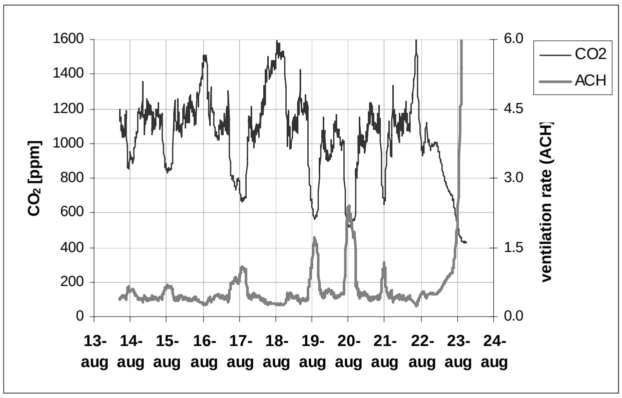

Figure 3 CO_2-concentration measured and ventilation rate calculated (expressed in ACH). The drop in the CO_2 concentration at the end is due to the draining of the CO_2-container.

ECOBUILD RESEARCH FACILITY

The 'Ecobuild' research facility, shown in figure 4, consists of a row of four dwellings that are typical for the type of dwelling built in the Netherlands. It serves to test various types of HVAC (Heating Ventilation and Cooling) systems. Dwelling A, to the left in figure 4, is of brick and cellular concrete construction and is heated by a gas-fired boiler.

Figure 4 'Ecobuild' research facility. Dwelling A is the one on the far left.

A data acquisition system, similar to that in the façade research facility, gathers experimental data every 10 minutes. CO_2 is injected incidentally to measure air tightness.

SIMULATION

Two building simulation models are used to describe the thermal processes in the research facilities. One is the 'Pascal' model. The other is the internationally accepted and validated building simulation model TRNSYS, that is used as a reference. After a description of the 'Pascal' model and its input, the main differences between TRNSYS and the 'Pascal' model are briefly discussed.

THE PASCAL MODEL

The 'Pascal' model calculates the response to a number of heat gains and heat losses. Heat gains are 1) internal heat production and 2) solar heat. Heat losses are due to 1) heat conduction and 2) ventilation and infiltration. How these heat gains and losses are determined from the experimental data is discussed further below.

The heat gains and heat losses will affect the indoor (mass) temperature. This is put into effect by first calculating the total thermal mass from all building materials used. The total thermal mass is then divided into two masses, a so-called *indoor* mass and an *outdoor* mass. These masses, which are generally at different temperatures, exchange heat through a heat resistance. The whole model can be represented as a three-temperature-node model, schematically shown in figure 5.

In the model, solar heat and internal heat production are represented as heat flows that will tend to raise the indoor mass temperature. Ventilation and infiltration losses will cool the inner fabric of the room and thus will tend to lower the temperature of the indoor mass. These losses can be represented by a heat resistance, since they are proportional to the difference between indoor and ambient temperature. Conduction losses on the other hand initially lower the outer fabric of the building, thus lowering the temperature of the outdoor mass. These losses too are proportional to the difference between indoor and ambient temperature and may be represented by a heat resistance R_{cond} (strictly speaking, the dimension of R_{cond} in figure 5 is K/W rather than m^2K/W).

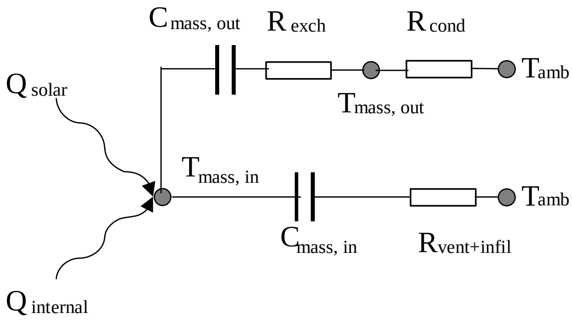

Figure 5 Three-temperature-node representation of the 'Pascal' building simulation model. The indoor mass temperature $T_{mass, in}$ is connected through an RC-element to the ambient temperature T_{amb} and through another RC-element to the outdoor mass temperature $T_{mass, out}$. To the left are heat flows Q_{solar} and $Q_{internal}$.

The value of the heat resistance R_{exch} between indoor and outdoor mass temperatures is determined by the general relationship:

$$R_{exch} = A/(d \cdot \lambda) \qquad (1)$$

where A is the total indoor wall area (in m^2), d the distance between both masses (in m) and λ the specific heat conductivity of the material between them (in W/m·K). Since both masses are (yet) imaginary, the distance and the type of material between them are subject to some guesswork. As an initial guess, d is set to 0.2m and λ to 0.1 W/m·K (average of wood and insulation material). The optimum value of R_{exch} is determined by trial and error.

The value of R_{exch} that best describes the thermal behaviour of the rooms in the façade research facility was determined in an earlier experiment in November 2003, using a PRH (Pseudo Random Heating) schedule (Dijk et al., 1995). The value found is used in all consequent experiments. The optimum value for the Ecobuild research facility is determined from a single experiment.

In the same way (by optimising the agreement between model and experiment), the relative size of the indoor and outdoor masses is empirically determined. Values for R_{exch} (or rather d·λ) and the indoor mass fraction are shown in table 1 for both research facilities.

INPUT TO THE PASCAL MODEL

The 'Pascal' model is fed with experimental data from the research facilities. How the input to the 'Pascal' model is determined from the raw experimental data is described below.

Internal heat production

The heat dissipated inside each room (due to the heating system, lighting, PC and other electrical equipment) is measured with kWh-meters and directly fed into the model.

Solar heat

The solar irradiation, incident on the vertical plane of the façade is measured with a pyranometer attached to the outside façade. The amount of solar heat entering the room is calculated from the area and the g-value of the glazing, (using a constant day averaged value) and the g-value of the sun shading (if the sun shading is down, which is monitored with a micro switch).

The g-values of the glazing and the sun shading are determined experimentally by measuring the ratio of indoor and outdoor irradiance levels (on a vertical plane) using two pyranometers. In addition, the indoor surface temperature of the glazing is measured to include the secondary heat transfer due to the heating of the glazing.

Heat conduction

The resistance to heat conduction R_{cond} is calculated from the thermal insulation of the building materials. As an initial value, the total conduction losses (in W/K) are determined from the areas of walls, floor, ceiling, glazing, window frame etc. and the theoretical insulation value of the materials used. When carrying out simulations with the 'Pascal' model, the value for R_{cond} is slightly adapted (by 10-20%) in order to avoid long term deviations between calculated and measured indoor wall temperatures. Throughout each experiment, a fixed R-value is used.

Ventilation and infiltration

Usually, a distinction is made between ventilation (deliberate air changes to control indoor air quality) and infiltration (uncontrolled air changes due to leaks, cracks, crevices etc.). The number of air changes is experimentally determined from an analysis of the indoor CO_2 concentration, as mentioned previously. In this procedure, ventilation and infiltration cannot be distinguished, so they are taken together. The value of the heat resistance that accounts for these losses, is calculated each time step (10 minutes) from the air change rate and properties of air.

The main parameters are summarized in table 1 below.

Table 1
Main parameters in the 'Pascal' model.

PARAMETER	**VALUE FOR 1 ROOM IN THE FAÇADE RESEARCH FACILITY**	**VALUE FOR THE ECOBUILD A RESEARCH FACILTIY**	**DIMENSION**
Total thermal mass	6.0	67	MJ/K
Indoor thermal mass as fraction of total thermal mass	30%	60%	-
Indoor wall area A	80	450	m^2
$d \cdot \lambda$ (=A/R_{exch})	0.2x0.15	0.2x0.15	W/K
R_{cond}	6.7	6.4	m^2K/W
Glazing area	2-3 *	13	m^2
g-value of glazing	50-60% **	59%	-
g-value of sun shading	15-70% ***	100%	-

* Depending on the façade

** Depending on the type of glazing in each façade

*** Depending on the type of sun shading, no sun shading in the 'Ecobuild' facility

TRNSYS

In general, TRNSYS is a much more sophisticated model than the 'Pascal' model. For instance the latter uses a constant g-value for the glazing instead of an angle dependant value as TRNSYS does. Other than the degree of sophistication, there are a number of differences between TRNSYS and the 'Pascal' model that are worth mentioning.

- In TRNSYS, the façade research facility is modelled in five different thermal zones (four rooms and the staircase). The 'Pascal' model is a one-zone model, so each room is separately modelled.
- Likewise, in TRNSYS, the Ecobuild dwelling is modelled in three thermal zones (one for each floor). In the 'Pascal' model, the dwelling is modelled as a single thermal zone.
- The building materials used are fed to TRNSYS using a layer library, instead of using general values such as R_{cond} for conduction losses or the g-value of glazing.
- TRNSYS uses its solar radiation processor to convert the solar irradiation on a horizontal plane (measured in the weather station) into the irradiation onto the façades, distinguishing between direct and diffuse irradiation. The 'Pascal' model uses directly the measured total irradiation onto the vertical plane of the façade.
- The effect of the building mass in TRNSYS is incorporated using heat transfer functions instead of a pair of coupled building masses.

RESULTS

The main criterion for the quality of the building simulation models is how well the actual thermal behaviour of the buildings is described by the models.

From a starting point, the models calculate the variations of the indoor wall temperature on the basis of experimentally determined heat gains and heat losses for periods of a week up to a month. This is called the *calculated* indoor wall temperature. In the case of TRNSYS, the indoor wall temperature is represented by the ceiling temperature calculated.

The indoor wall temperature is also experimentally determined by taking the average of the measured temperatures of side walls, hind wall, floor and ceiling. This is called the *measured* indoor wall temperature.

In the following chapters, the *calculated* indoor wall temperature is compared to the *measured* value, to assess the quality of the building simulation models.

RESULTS FOR THE FAÇADE RESEARCH FACILITY

An example of calculated and measured indoor wall temperatures is presented in figure 6 for one of the rooms. Both the results of the 'Pascal' model (dark grey line) and TRNSYS (light grey line) are shown. Due to an interruption of the dataflow from the horizontal pyranometer, the TRNSYS simulation ends on August 21.

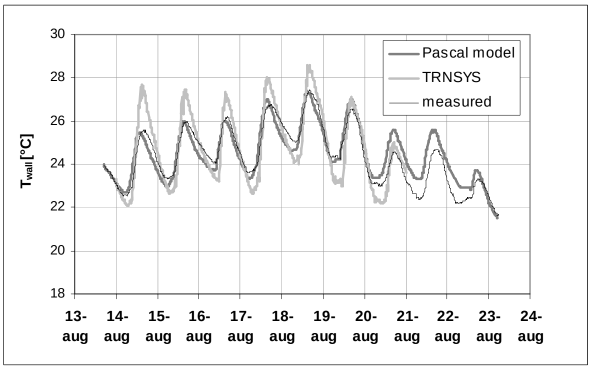

Figure 6 Calculated and measured indoor wall temperature for the case of room nr. 2, oriented towards the south. At night, the window was opened for night cooling.

Figure 7 shows the case of another room, where no night cooling was applied. The indoor temperature drop during the night, caused by conduction and infiltration losses, is roughly half the value found for the case with night cooling.

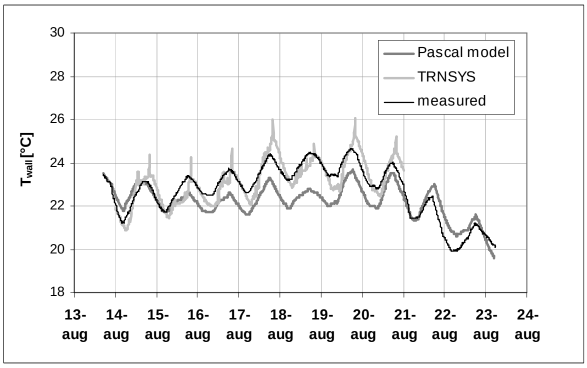

Figure 7 Calculated and measured indoor wall temperature for the case of room nr. 1, oriented towards the north, without night cooling.

The temperature variations that TRNSYS calculates in figure 6 are too high. Here, the output of the 'Pascal' model agrees better with the experimental data. On the other hand, the TRNSYS output agrees better with the experimental data in figure 7.

Both models however appear to be able to calculate values for the indoor wall temperature that generally differ less than 1°C from the measured value. Both models can therefore be said to adequately describe the thermal behaviour of the rooms.

In addition to the *indoor* mass temperature shown in figures 6 and 7, the Pascal model also calculates the *outdoor* mass temperature. Both indoor and outdoor mass temperatures are shown in figure 8 for the case of room nr. 2.

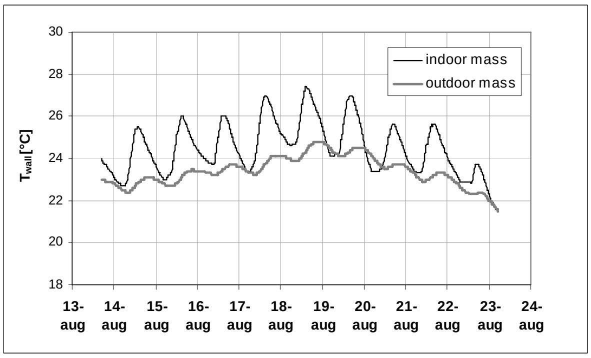

Figure 8 Variation of indoor and outdoor mass temperature, calculated for the case of room nr. 2.

Apparently, diurnal temperature variations are mainly determined by the indoor thermal mass, while the long-term variations are determined by both indoor and outdoor mass. Variations in indoor mass temperature are so to speak superimposed on the variations of the outdoor mass temperature.

Another interesting form of output of the 'Pascal' model is the energy balance over a certain period of time, as shown in figure 9.

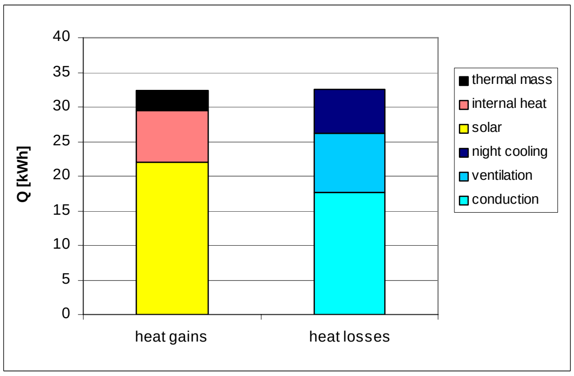

Figure 9 Energy balance of room nr. 2 for the period of 13-23 August 2004.

The column on the left shows the heat gains in the particular period. These are solar heat and internal heat production, and in this case, heat from the thermal mass. Apparently, the temperature of the room at the end of the experiment was lower than the temperature at the start (see also figure 8), so part of the heat losses were at the expense of the temperature of the thermal mass(es). Heat losses are conduction losses, ventilation and infiltration losses (during the daytime) and heat losses as a result of night cooling.

The energy balance is very instructive. It shows for instance that in this particular experiment the major contribution to heat losses are the conduction losses and the major contribution to heat gains is the solar radiation. It is a powerful aid in focussing the effort to improve the thermal performance of a room, or in general, a dwelling.

It should be noted that the energy balance in figure 9 is not representative of a regular dwelling. In general, the degree of thermal insulation, ventilation regime, internal heat production etc. will differ from those in this particular experiment.

Instead of using a particular set of experimental data as input to the 'Pascal' model, a more general dataset, such as that of the test reference year can be used. This dataset contains hourly values for ambient temperature, solar radiation, wind speed etc. in the course of a year, that are representative of the national or local climate. Instead of a micro-switch signal indicating the window being open or closed, a control strategy for opening windows for night cooling can be used. This way, the control strategy decides if certain criteria for opening the window are met. When this is the case, the model assumes a certain ventilation rate as a result of opening the window. Thus, the effect of different strategies for night cooling (e.g. the one shown in figure 10) on overheating can easily be assessed.

Control strategy for night cooling
Open windows **if**
T_{indoor} > 23°C **and**
$T_{indoor} - T_{ambient}$ > 4°C **and**
Time between 11 p.m. and 6 a.m.
Close windows **if**
T_{indoor} < 18°C **or**
$T_{indoor} - T_{ambient}$ < 3°C **or**
Time **not** between 11 p.m. and 6 a.m.

Figure 10 Example of control strategy for night cooling.

RESULTS FOR THE ECOBUILD FACILITY

To see if the Pascal model can also yield acceptable results for the case of a building more complex then a single room, the model is applied to test data from the Ecobuild research facility. This is carried out for a single experiment in October 2004. The same type of experimental data as for the case of the façade research facility is used as input to the model. In figure 11, the indoor wall temperature, calculated by both the 'Pascal' model and TRNSYS are compared to the temperature, measured by a sensor mounted in the ground floor ceiling.

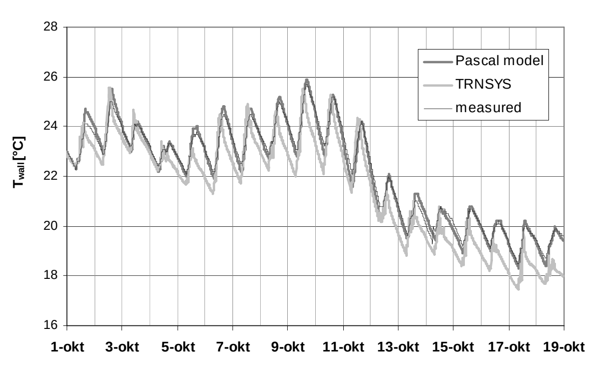

Figure 11 Calculated and measured indoor wall temperature for the Ecobuild A dwelling.

Applying the 'Pascal' model to a single experiment allows optimising the parameters for this particular case. This may be part of the reason for the excellent agreement between the measured and calculated indoor temperatures.

DISCUSSION AND RESULTS OF THE ANALYSIS

In all 'Pascal' model calculations (for both the façade research facility and the Ecobuild research facility), three parameters are varied to optimise the agreement between calculated and measured wall temperatures: 1) the value of R_{cond}, 2) the heat resistance between indoor and outdoor mass (R_{exch} or $d \cdot \lambda$) and 3) the indoor mass fraction.

The value of R_{cond} only serves to avoid long term deviations between calculated and measured indoor wall temperature. The R-value empirically found is 10-20% lower than the value estimated from the building materials used. This is not surprising as the estimation is a simple and straightforward one, not taking into account complex construction details, nor thermal bridges or flaws in the construction process (e.g. cement dropping in the cavity, gaps between insulation sheets etc.).

Although the type of construction is quite different for the façade research facility (timber frame) and the Ecobuild research facility (cellular concrete frame), the value found for $d \cdot \lambda$ is the same for both and can be accounted for on physical grounds. It indicates that the parameter R_{exch} has some physical meaning rather than being just another parameter in a parametric model.

The values found for the indoor thermal mass as a fraction of the total mass are very interesting. The indoor mass can be related to a material volume from which an effective wall thickness can be calculated when the total indoor area (walls, floor and ceiling) is known.

For the façade research facility, a gypseous wall material (heat capacity 1.4 MJ/m^3·K) is assumed. For the Ecobuild facility, the matter is a little more complicated. The walls are made of cellular concrete while the floor and ceiling are made of concrete. The thickness calculated depends on whether the heat capacity of cellular concrete (0.7 MJ/m^3·K) or concrete (1.6 MJ/m^3·K) is used. The results are shown in Table 2 below.

Table 2
Indoor thermal mass from the 'Pascal' model related to an effective wall thickness.

GEOMETRY	INDOOR THERM. MASS [MJ/K]	INDOOR AREA [M^2]	EFF. WALL THICKNESS [CM]
Room in façade research facility	1.8	85	1.5
Ecobuild A dwelling	40.2	465	5-12 *

* Depending on whether cellular concrete or concrete is assumed.

For the room in the façade research facility, an effective wall thickness of 1.5 cm is found, which corresponds more or less to the thickness of the gypsum boards used to finish the inside of the rooms. Apparently, it is mainly the gypsum board that determines diurnal temperature variations.

For the Ecobuild dwelling, a thickness of 5 to 12 cm is found, depending on whether concrete or cellular concrete is assumed. This value corresponds to values found in (Keller, 1997). Apparently, for concrete frame constructions, the inner 5-12 cm of material determine the diurnal temperature variations.

Although the number of buildings investigated (2) is small, it appears that for a new building, the value of the 3 parameters can be readily calculated. R_{cond} can be calculated from the area of the building envelope and insulation values (walls, windows etc.), perhaps taking 10% to account for thermal bridges and other imperfections. The value of $d \cdot \lambda$ to calculate R_{exch} may be left unchanged (at least for buildings that are thermally well insulated). The total thermal mass and indoor thermal mass may also be directly calculated from the building materials, using the effective thickness as calculated in table 2.

The main advantage of following this procedure, rather than feeding all materials and their properties to a model, is that insight may be gained into which parameters determine the thermal behaviour of a dwelling.

Summarizing, the simple 'Pascal' model appears to be quite able to describe the thermal behaviour of the rooms in the façade research facility as well as that of a more complex dwelling. In addition, the results for these cases are comparable to those of the much more sophisticated building simulation program TRNSYS.

The latter is not particularly surprising. The results of any simulation stand or fall with the quality of the input. Even in the case of well-controlled experimental rigs as our research facilities, it appears to be quite a challenge to obtain accurate data as input to the models. Uncertainties are found in ventilation and infiltration rates, solar irradiation, cold bridges etc. These have such a large effect on the outcome, that any program, including a highly sophisticated one, is limited by the quality of the input.

SUMMARY AND CONCLUSIONS

A simplified building simulation model (the 'Pascal' model) has been developed. To validate the program, it is applied to two ECN research facilities and its output is compared to measured data. In addition the results are compared to those of the building simulation model TRNSYS.

The 'Pascal' model appears to be able to adequately describe the thermal behaviour of the façade research facility as well as that of a realistic and more complex Ecobuild dwelling. In the cases studied, its performance is comparable to that of the much more sophisticated building simulation model TRNSYS.

The 'Pascal' model shows that diurnal temperature variations are mainly determined by the so-called *indoor* thermal mass, while long term temperature variations, such as those found during a summer heat wave are determined by the total thermal mass. The indoor mass in the façade research facility corresponds to the thermal mass of the gypsum board finish on the inside of the rooms, while the indoor mass in the Ecobuild dwelling corresponds to a concrete wall of 5 cm thickness. These are values one would expect for a lightweight building, such as the façade research facility, and a heavy building, such as the Ecobuild dwelling.

With the model, different strategies for sun shading, night cooling etc. can easily be assessed, in particular for a dwelling with 'active' facades.

The energy balance, which the 'Pascal' model supplies, is very instructive, showing the relative importance of the different heat gains and heat losses. It is thus a powerful aid in focussing the effort to improve the thermal performance of a dwelling,

In summary, the 'Pascal' model combines the simplicity and understanding of easy to use programs with the flexibility and possibilities of advanced programs.

NOMENCLATURE

A indoor wall area [m^2]

C thermal mass [J/K]

d distance between in and outdoor mass [m]

Q heat flow [W]

R resistance to heat flow [m^2 K/W]

T temperature [K]

λ specific heat conductivity [W/m K]

Subscripts

AMB ambient

COND conduction

EXCH exchange

INFIL infiltration

VENT ventilation

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