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Passive Cooling, Simulations and Experiences from Realized Projects in Sweden

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Abstract.

The use of computers for simulating building thermal behavior started early at the Royal Institute of Technology in Stockholm, Sweden. The first example of such use dates from a 1957 study of an exterior wall exposed to solar radiation.

The simulation program, later named BRIS, has gradually evolved with regard to the users and growing computer capacity. It has been used since the early sixties for research projects, design work and development of new systems, among others the ventilated hollow-core slab (Thermodeck) system.

In 1990 the originators of BRIS recieved Swedish Great Energy Award for "distinguised contributions in the field of energy conservation". The jury stated that the knowlege we got from the simulations has lead to an annual saving of energy worth 100 millions Swedish Crowns.

BRIS contains different installation- and control components representing generic models rather than specific implementations. The components can be combined freely to correspond to the principal operation of any HVAC system.

The control strategy is based on a sequence of restrictions on the possible sources for heating, cooling or heat recovery. The restrictions are relaxed successively within each time step in the building model until a solution is found. The order in which the restrictions are to be relaxed may be varied, the capacity intervals can be open ended on one side, etc.

By combining loads and systems minimum energy strategies can be defined and found by the program. When limiting the installed capacities the building dynamics will be more active in the control process which has shown to give a surprisingly high potential to reduce peak power problems and energy use.

We now have experience from over 300 buildings using the Thermodeck system for passive cooling. Some of theese experiences are reported and commented in this paper.

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Background.

Many load calculation methods or computer programs cannot be directly employed for thermal storage systems. In Sweden research has been focused on the technique of using building mass since the late fifties. A computer program, BRIS, was developed at the Royal Institute of Technology in Stockhom with support from the Swedish National Board of Building Research. The program was based on fundamental physical relationships and finite difference techniques (Crank - Nicolson) were used to solve the Fourier equations and the boundary conditions were treated in detail. BRIS has been developed continuosly with regard to the users and growing computer capacity.

The control strategy is based on a sequence of restrictions on the possible sources of heating, cooling and ecomomizer cycles. The restrictions are relaxed successively within each time step in the building model until a solution is found.

By combining loads and systems minimum energy strategies can be defined and found by the program. When limiting the installed capacities the building dynamics will be more active in the control process which has shown to give a surprisingly high potential to reduce peak power problems and energy use without sacrificing (maybe rather improving) the comfort.

Among serious consultants BRIS is a natural tool in the design process today and we have seen about one thousand results in the shape of real buildings.

Significant energy savings have been realized and in 1990 the originators of BRIS recieved the Swedish Great Energy Award for "distinguised contributions in the field of energy conservation".

Passive technology is a well known concept today, but still many buildings with very complicated and oversized HVAC systems are built. Energy costs and peak - power problems now lead to a wakening need to improve the competence and reintroduce the physical laws in the design process.

Now the next generation of BRIS, called IDA, is being developed.

This is a modular system for applications on different complicated processes. For description of the mathematical component models a special format, the Neutral Model Format (NMF) has been developed. NMF models are program neutral and can be automatically translated into the formats required by a number of different simulation environments such as IDA, TRNSYS, HVACSIM+ and SPARK. Based on NMF, environment independent application libraries can be established. ASHRAE has assumed the responsibility of maintenace.

Experiences from realized projects.

There is a large potential in utilizing the building dynamics together with installed equipment for climatisation. The basic philosophy is to work with nature instead of against it.

Accordingly the experience from buildings where BRIS has been used in the design work (most governmental, official and private business buildings downtown Stockholm) is that high comfort can be provided even with very low installed capacities for cooling (1/2 or 1/3 compared to buildings where more conventional design tools have been used). Also in hot, arid climates considerable savings have been done.

However, the utilization of building dynamics is poorly understood in practice today. Also modern, advanced control systems seem to have recoiled upon the ambition to maintain constant temperatures or to force the temperature to follow special schedules. If there are large capacities for heating and cooling available this could lead to peak power problems and a tremendous waste of energy. On the other hand, effective climate control often can be achieved with modest capacity and much less energy if passive techniques and the building mass are incorporated in the control policy. This is shown in the following example:

Example.

Office 10 m^2, surrounded by similar rooms:

Exterior wall: 12.5 cm brick

12 cm of mineral wool

10 cm of concrete

Partitions: 2*13 mm of plaster board

Floor-ceiling slab: 20 cm of concrete,

Window: 1.8 m^2 (glass area), three panes of ordinary window glass. Venetian blinds between the outer panes.

Outdoor temperature: 19±6 °C max. at 3 PM.

Air flow rate: 5 ACH.

Remark: From the energy efficiency point of view this is a very high value. More common today is 0.5 ACH compensated by fancoils or cooling panels for heat extraction. Due to the sick building problem the supply air flow rate is now being discussed, and will probably increase in the future.

Infiltration: .2 ACH

Solar (Stockholm July South) and internal heat gains during the office hours are shown in Fig. 1.

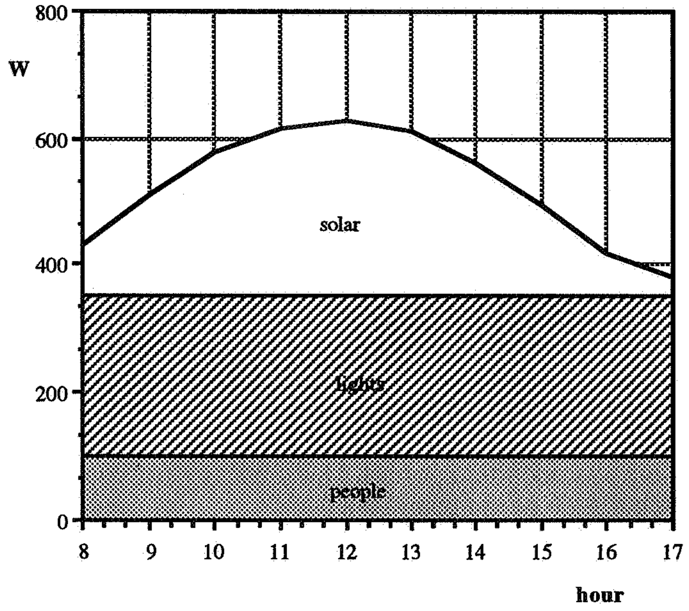

Fig. 1. Heat gains. Maximum value = 626 W.

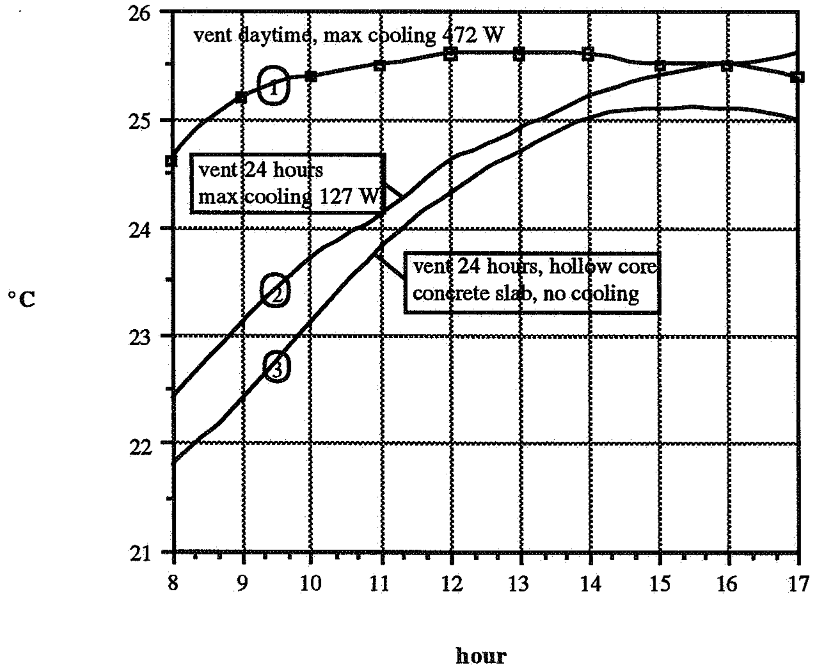

Fig. 2. Effective temperatures during the office hours using different control strategies.

Curve 1: Here we see a control policy typical in many modern buildings. The cooling system is operating only during occupied periods, and the control system is designed to maintain constant, 25 °C, room air temperature. The effective temperature is higher due to radiation. The cooling coil load is large, 472 W. Daily energy for cooling: 3.11 kWh + fanpower 0.50 kWh = 3.61 kWh.

Curve 2: Now we operate the equipment continuously. Space effective temperatures are cooler in the early occupancy hours due to lower surface temperatures, but still well within comfort range. These lower surface temperatures also mean lower capacity and energy required for cooling throughout the day. Also, since the additional hours are mostly during cooler hours, some of the cooling can be provided with outdoor air (economizer cycle). To see if we can go further with this strategy, we have stepwise reduced the installed capacity to 27 % of the original, and use a 22 °C set point. We see that we still are well within comfort conditions throughout the occupied period. Daily energy for cooling 1.66 + 1.09 = 2.75 kWh (76 % of the original).

Curve 3: Finally we reduce the cooling coil capacity to 0 and compensate by letting the supply air pass the holes in hollow core concrete slabs (Thermodeck). The stronger thermal coupling between the air and the mass gives a better use of the thermal capacity. The comfort is better without cooling than in the original case. Daily energy use for cooling 1.09 kWh (only fanpower).

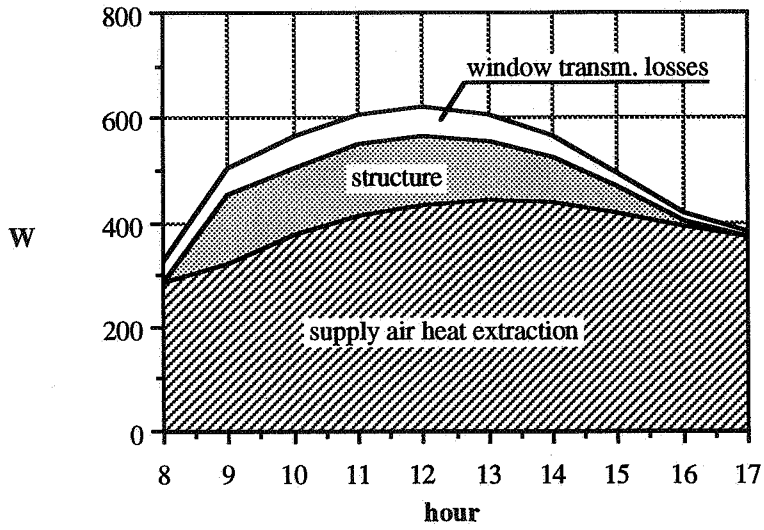

Fig. 3. Negative items in the room heat balance when the cooling system operates only at daytime. Set point 25 °C. The major part of the heat gains are extracted by the

zone supply air (maximum 442 W). Only 136 W is stored in the structure (coming back at night). Required cooling coil capacity is 472 W. The effective temperature exceeds 25 °C during more than 8 of 9 office hours, see curve 1 in Fig. 2.

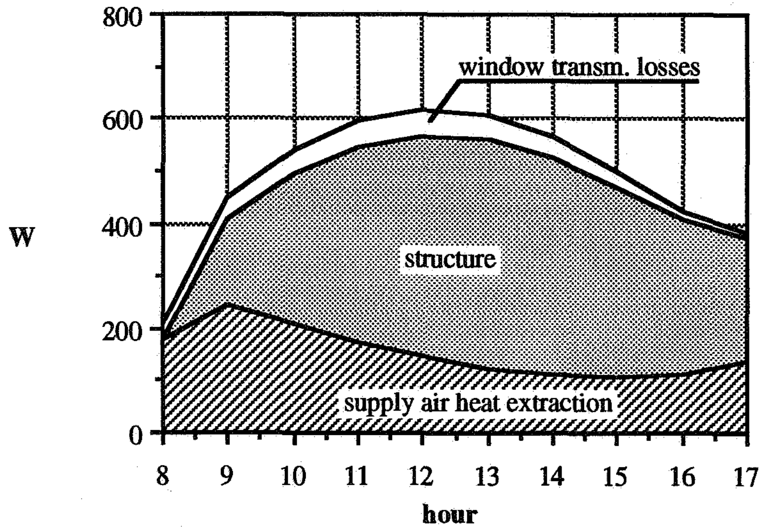

Fig. 4. Negative items in the room heat balance when the cooling system operates continuously. Set point 22 °C. A smaller part of the heat gains are now extracted by the supply air (maximum 243 W) and 435 W is stored in the structure. Required cooling coil capacity is reduced to 127 W (27 %). Still the comfort is improved, see curve 2 in Fig. 2.

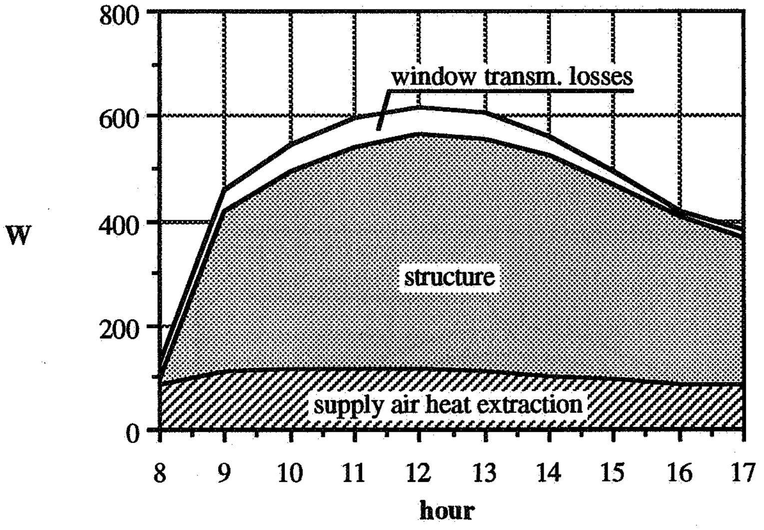

Fig. 5. Negative items in the room heat balance when using ventilated hollow core concrete slabs and no cooling. The structure is fully utilized and takes care of more than 75 % of the gains in the afternoon.The comfort is better than in the original case, see curve 3 in Fig. 2.

A simple one-mass model for estimating the performance of ventilated hollow core slabs.

Energy saving in modern Scandinavian office buildings is a matter of storing excess heat from daytime to cover heat losses during the night. The heat capacity of concrete slabs is mostly sufficiently high to store and emit enough energy to keep rooms within a comfortable temperature range.

However, the slabs are not always available for heat storage, due to soft carpets and suspended ceilings which introduce thermal resistance at the surfaces.

A Swedish system called the Thermodeck system utilizes hollow core slabs to reach the storage capacity from the inside. The supply air passes through the holes in the concrete before it enters the room. Laboratory measurements have shown that the temperature gradients along the slab are small compared to the temperature difference between the incoming and outgoing air. To show how different parameters affect the performance of this system a simple one-mass analytical model is used.

The mass is supposed to be concentrated in a thin sheet with a uniform temperature.

The incoming air varies sinusoidally:

$$\upsilon_{in} = a \cdot sin(\omega t)$$

where

a is the amplitude, °C

ω angular velocity, h^{-1}

t time, h

(for a 24-hour oscillation $\omega = \pi/12$)

The mass temperature and outgoing air temperature are damped and delayed

$$\upsilon_{mass} = \frac{a}{Z_m} \cdot \sin(\omega t - \phi_m)$$

$$\upsilon_{out} = \frac{a}{Z_{out}} \cdot \sin(\omega t - \phi_{out})$$

The air temperature along the slab is assumed to change exponentially towards the slab temperature.

With $\alpha = exp(-\frac{hA}{V\rho cp})$

and $\beta = \frac{V\rho cp}{MC}\,(1-\alpha)$

the solution of the differential equation that this model gives rise to

is:

$$\phi_m = arcsin\left(\frac{\omega}{\sqrt{\beta^2 + \omega^2}}\right)$$

$$Z_m = \frac{1}{cos(\phi_m)}$$

$$\phi_{out} = arctan\left(\frac{cos(\phi_m)\ sin(\phi_m)\ (1-\alpha)}{cos^2(\phi_m)\ (1-\alpha)+\alpha}\right)$$

$$Z_{out} = \frac{sin(\phi_{out})}{cos(\phi_m)\, sin(\phi_m)\, (1-\alpha)}$$

Here

$V =$ air flow, m^3/h

$\rho =$ air density, kg/m^3

$c_p =$ specific heat capacity of air, Wh/kg,°C

$M =$ slab mass, kg

$C =$ specific heat capacity of the slab material Wh/kg,°C

$h =$ film coefficient, W/m^2,°C

$A =$ area, m^2

The unknown parameter in this model is the film coefficient h. To examine how it affects the time lag and the damping we now chose a 10 m^2 slab ventilated by 100 m^3/h as an example. The mass is supposed to be 4600 kg (20 cm of concrete, $C = 0.24$ Wh/kg,°C).

When $hA = 0$ the mass temperature is constant, and the outtgoing air temperature follows the incoming air temperature. With an increasing hA-value the air temperature variation is more effectively damped and delayed. The mass temperature starts varying sligtly with a delay close to 90 ° (= 6 hrs), the highest possible value for a 24 - hours swing.

The time lag and damping of the outgoing air temperature variation are plotted in fig. 6 and 7 respectively.

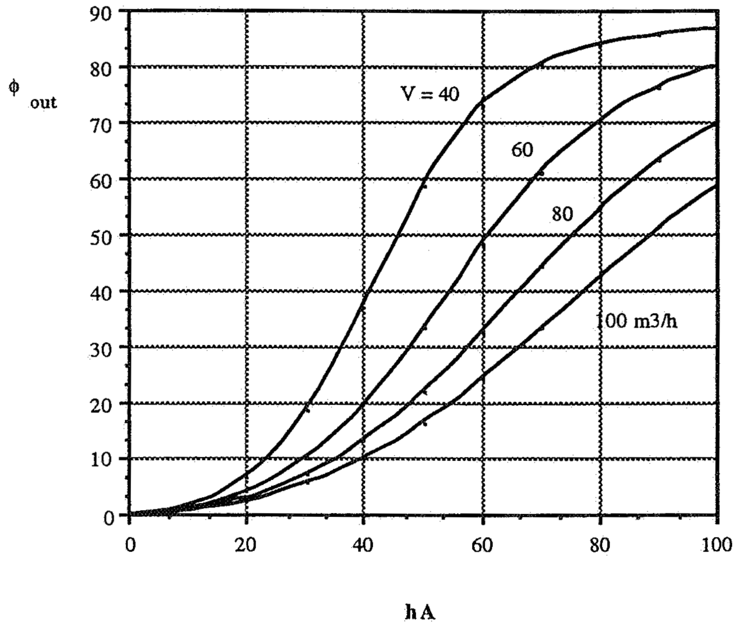

Fig. 6. Time lag in outgoing air temperature. 90° = 6 hours.

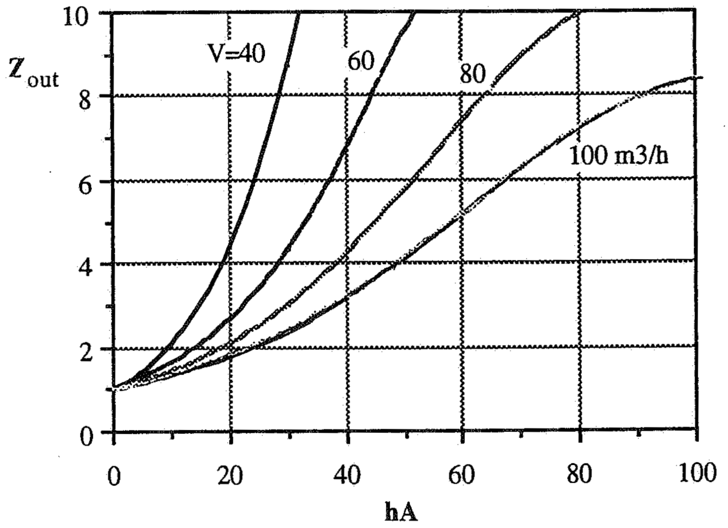

Fig. 7. Damping of amplitude incoming/outgoing air temperature.

It is obvous that the value of hA has a strong influence on the performance of this system. This value depends on the hole diameter, the number of holes, and the air velocity.

The film coefficient for straigt channels can be obtained from the expressions

$Nu = 0.032 * Re^{0.8} * Pr^{0.30} * (D/L)^{0.054}$

for turbulent flow and

$Nu = 0.578 * Re^{0.5} * Pr^{1/3} * (D/L)^{0.5}$

for laminar flow.

We use the equations on the following standard element which is manufactured in many countries:

length	$L = 5$ m
breath	1,2 m
thickness	0,28 m
5 holes diam.	$D = 0{,}18$ m

The holes are connected in series.

For this element we get the results shown in Figs 8- 9.

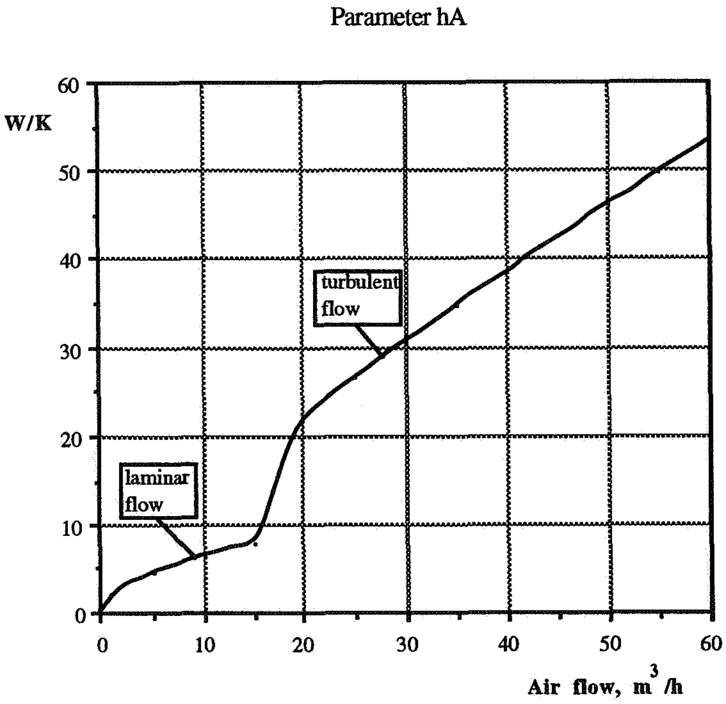

Fig 8. Convective heat transfer inside the holes. Hole diameter 0.18 m.

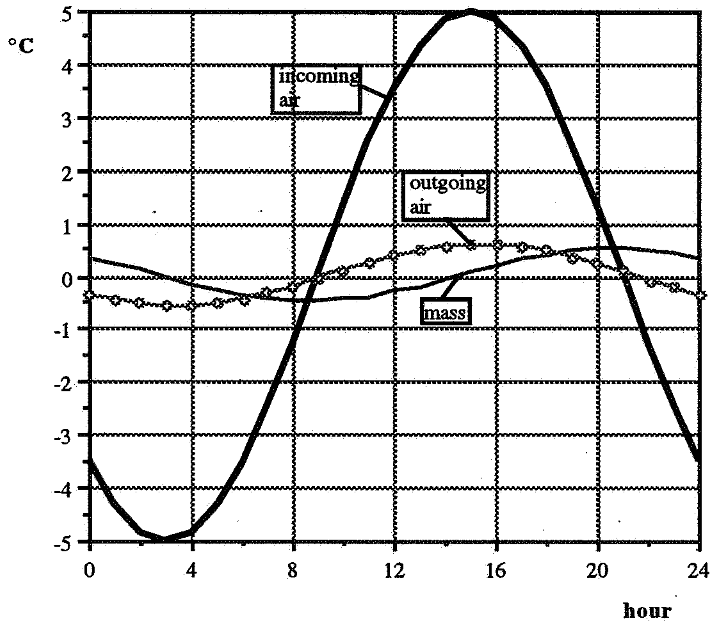

Fig. 9. Temperature variation of incoming - outgoing air and mass. Air flow rate 40 m^3/h.

In a building any element is exposed to disturbances by heat exchange from the room via the floor- and ceiling surfaces, and in the BRIS program the model presented above defines the boundary conditions on the inside of the holes.

Conclusions.

It is now time to use simulation programs and knowledge from the use of these tools not only for the design of systems meeting requirements from an uninformed builder, but also to convince him what poorly formulated requirements will cost him.

More cooperation with the control engineers is also necessary. Computerized control systems have a high potential, and could be used not only for prompt compensations, but for advanced smoothing and forecasting techniques. Energy supply or extraction could then be made using low powers during long periods, for instance during the night hours, to prepare the building for the next morning. Peak periods can be avoided until it is necessary. In between, the building takes care of itself.

A proper use of simulation programs will show how the building dynamics can be utilized and result in much more energy and power efficient buildings in the future.

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