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Simulation for Design: Comparing Two Low-Energy Cooling Strategies for an Atrium

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1. INTRODUCTION

As argued before (Hensen 1993), the built environment is rather complex and involves many interactions. Even when we limit ourselves to energy, environmental and comfort issues, real building design questions are usually too complicated to be solved using simple rules or design guidelines. One way of dealing with this complexity is by using computer modelling and simulation. This paper aims to demonstrate the use of computer simulation for building design by means of a case study.

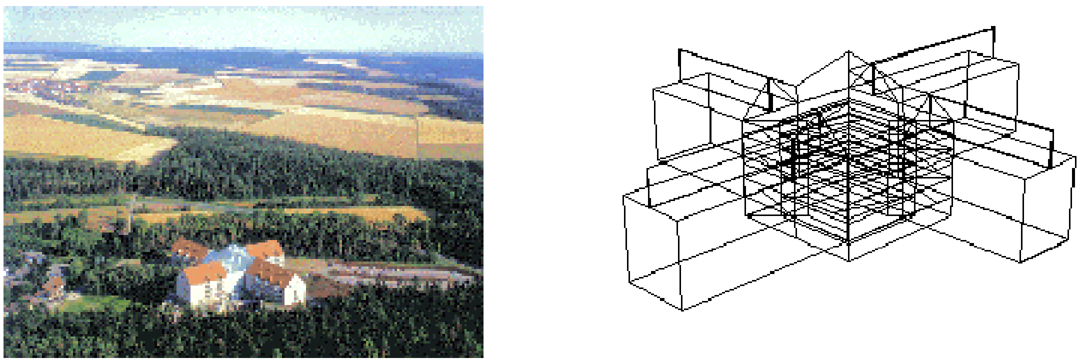

Figure 1 Aerial view of the building and graphic feedback of the computer model in the ESP-r modelling and simulation environment (ESRU 2000)

The case (Hensen et al. 1995) concerns summer comfort problems in the central atrium of a neurological clinic in the centre of Germany; Figure 1. In order to reduce summer temperatures, two low-energy cooling strategies were considered: replacing the existing glazing system and/or increasing natural ventilation.

2. REPLACING THE GLAZING SYSTEM

In terms of alternative glazing systems, the following options have been considered:

- solar control glazing with lower solar transmittance than the existing glazing system;
- thermotropic glazing - which switches its optical properties as a function of temperature - with different sets of optical properties for the switched state (pessimistic and optimistic values) and

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assuming different switching temperatures.

2.1 Thermotropic Glazing

Thermotropic glazing in the simplest form consists of a glass laminate with an intermediate layer of thermotropic material. Thermotropic material transmits sunlight and heat at low temperatures but automatically "switches" to reflection at higher temperatures. The material consists of two main components with differing refractive indices (a polymer and water in the case of so-called hydrogels, and two different polymers for polymer blends). At low temperatures, these are mixed at the molecular level, so that the material is homogeneous and transparent. If the temperature in the material rises to a certain value, which can be set within limits during the production process, the two components separate into microscopic domains. Incident light is strongly scattered, with most of it being diffusely reflected. The layer turns white. Only a small fraction of the light is then transmitted.

In order to achieve acceptable thermal insulation (low U value), a thermotropic glazed laminate is used as the exterior pane together with a low-e coated interior pane in a gas-filled, sealed glazing unit. This type of glazing unit can be used to prevent overheating in summer, while allowing solar gains in winter (Georg et al. 1998).

There has been significant progress in the development of switchable glazing since the simulations were made in 1994/5. Prototypes of thermotropic hydrogel glazing have been produced in small quantities in Japan (Watanabe 1998). The second phase of a joint German project on thermotropic layers has focussed on improvement of water-free systems based on thermotropic polymer blends (Blessing and Wilson 1998).

Parallel to the developments in thermotropic glazing, with their automatic temperature-dependent change in transmittance, two approaches to "active" switching in response to an external signal have been intensively pursued. The first electrochromic architectural glazing was introduced to the European market in 1998 (Pilkington 1999). Gasochromic glazing has been developed to the prototype stage as an alternative offering higher transmittance in the bleached state (Georg et al. 1998). These two types of glazing retain visibility in the switched state, but require installation of more complex systems technology in the building facade than is the case for thermotropic glazing.

2.2 Computer Model

Modelling can be seen as the process of re-expressing the building design in a manner suitable for simulation. This process generally depends on whether the context is new building or retrofit; on the availability of dimensional, constructional and operational data; and on the objectives of the analysis. Unlike tasks such as visual impact modelling - where the goal is to attain realism - energy modelling can be carried out abstractly. For example, some complex shape may be simplified or rooms of similar temperature grouped into one zone. Although there is no hard and fast rule, it is usually sufficient to preserve surface areas, aspects and contained volumes so that the heat conduction, thermal capacity and spatial relationships are preserved. A rule of thumb is to represent the problem as simply as possible in relation to the required outputs, but in a manner that can be extended and refined should the need arise.

Table 1 Main optical (normal angle of incidence) and thermal characteristics of the glazing system. T_{vis} = normal-hemispherical visible transmittance; T_{sol} = normal-hemispherical solar transmittance; SHGC = nominal solar heat gain coefficient (indicative); U = nominal U-value (indicative).

Characteristic:	**T_{vis}** -	**T_{sol}** -	**SHGC** -	**U** W/m^2K
Existing glazing	0.43	0.29	0.39	1.76
Solar control, 66/34	0.65	0.30	0.33	1.20
Solar control, 21/20	0.21	0.134	0.20	1.3
Thermotropic, vertical, clear state	0.75	0.41	0.51	1.25
Thermotropic, roof, clear state	0.70	0.37	0.49	1.24
Thermotropic, switched state, pessimistic	0.17	0.10	0.16	1.3
Thermotropic, switched state, optimistic	0.05	0.03	0.06	1.2

The above approach was also adopted in the current case, which was modelled as shown in Figure 1. Although the model is as simple as possible, the configuration is still relatively complex, and the model comprises not less than 25 thermal zones for the atrium. Where there are no surfaces in reality, the thermal zones are bounded by fictive surfaces which do not absorb or reflect solar radiation; thus enabling solar radiation modelling inside the atrium. Adjacent spaces are taken into account assuming fixed thermal conditions, and as “solar obstruction blocks” as indicated in Figure 1.

Of particular interest in this case are the parameters related to the glazing system as given in Table 1. Since the optical properties of the thermotropic glazing in the switched state were still the subject of material development, optimistic and pessimistic assumptions were made. It should be noted that in the current study, all transparent systems were handled as so-called “transparent multi-layered constructions”. This means that simplified concepts such as U-value and "solar heat gain coefficient" are not used. The only data that are actually used are direct solar transmission and the solar absorption in each layer for various angles of incidence. From this data it is then possible to calculate the solar transmittance and the temperature of each layer in the transparent construction. From the temperature of the inside layer, the heat transfer coefficients, the room air and surface temperatures, and the convective and longwave heat fluxes from the window to the room (and thus implicitly the solar heat gain coefficient) are calculated.

3. INCREASING NATURAL VENTILATION

Currently the ground level entrance and balcony doors are opened if the atrium temperatures are high. This results however in draught and thus comfort complaints by staff and patients.

3.1 Natural Ventilation Ducts

In order to increase natural ventilation while at the same time avoiding draughts, the system shown in Figure 2 was considered. It was assumed that it would not be a problem to have the large roof windows open. Such a system will allow a large supply of cool fresh air at a low level in the atrium without any comfort complaints due to draught. Some initial simulations were performed in order to estimate the required dimensions of the ducts. From this it was found that 4 ducts, each 30 m long and 1 m^2 cross section, would be sufficient.

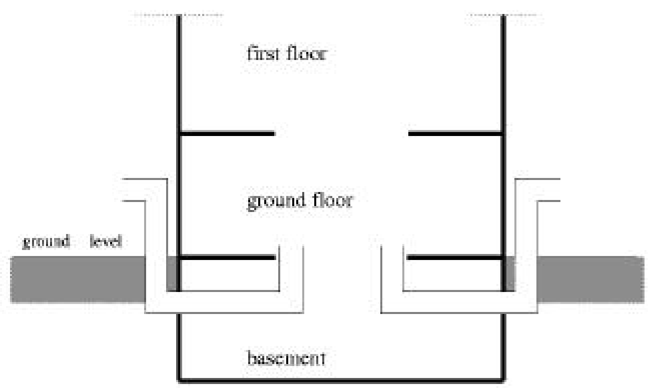

Figure 2 Sketch of natural ventilation ducts providing outdoor air to the core of the atrium

3.2 Computer Model

In building energy prediction, it is still common practice to separate the thermal analysis from the estimation of air infiltration and ventilation. This might be a reasonable assumption for many practical problems, where the air flow is predominantly pressure driven; i.e. wind pressure, or pressures imposed by a mechanical ventilation system. However, this simplification is not valid for cases where the air flow is buoyancy driven; i.e. involving relatively strong couplings between heat and air flow. Passive cooling by increasing natural ventilation to reduce summer overheating is a typical example.

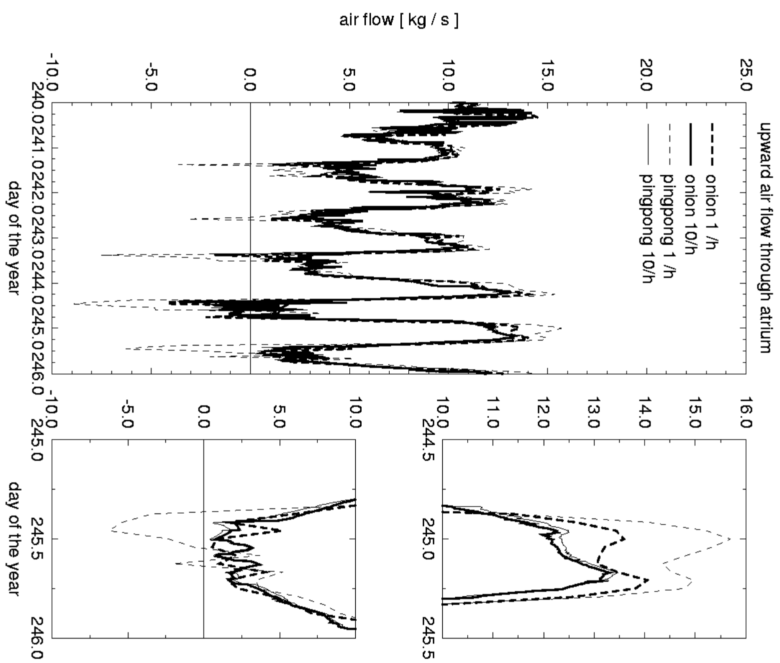

Figure 3 Simulation results for vertical air flow through an atrium during 6 days of a reference year. Smaller frames show selected results in more detail. "Onion" and "pingpong" refer to different modelling approaches. (From Hensen 1999)

Hensen (1999) elaborates the above and compares in some detail various coupled and de-coupled solutions for temperature and air flow in a building. It is also argued that in the context of combined heat and air flow simulation in buildings, the zonal mass balance network method is more effective than computational fluid dynamics techniques. Figure 3 (from Hensen 1999) shows some air flow simulation results for an atrium very similar to the one considered in the current paper.

Since it is counterintuitive for most people, it is interesting to note that the flows tend to be higher during the night than during the day. This is a result of the inside-outside temperature difference, which is larger during the night. The effect is less pronounced for the first day, which has relatively low ambient temperatures and solar radiation.

The above results are included here for illustrating the concept - and associated features - of natural convection cooling. The results of a comparative study between using and not using natural convection cooling are included in the following section.

4. RESULTS & DISCUSSION

Due to space constraints only a small selection of the results can be presented here. In terms of the various glazing systems, the simulations showed that the best summer performance (in terms of reducing internal air temperatures relative to the current situation[1]) may be expected from:

- thermotropic glazing; switch at 20 °C; optimistic data set

followed by:

- thermotropic glazing; switch at 20 °C; pessimistic data set
- solar control glazing 21/20
- thermotropic glazing; switch at 25 °C; pessimistic data set
- solar control glazing 66/34.

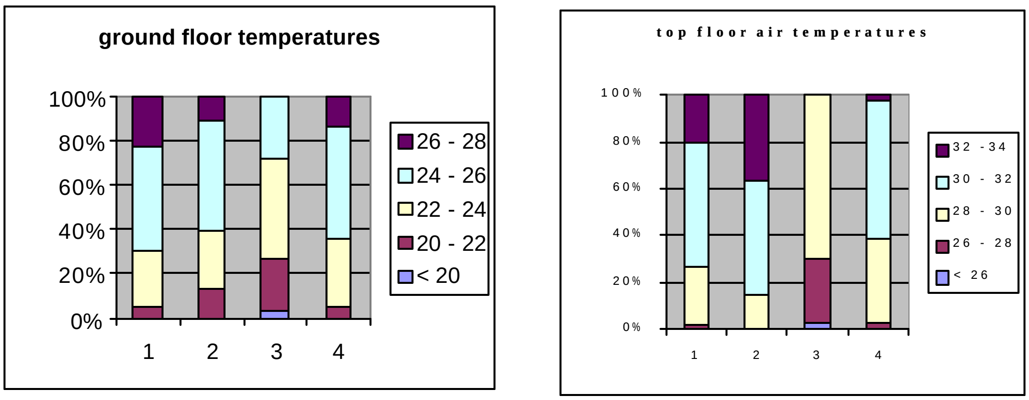

Figure 4 Summary of atrium air temperatures during a week in July for the cases: 1 = current glazing; 2 = solar control glazing 66/34; 3 = thermotropic glazing, switch at 20°C, pessimistic data set; 4 = current glazing + ducts.

For some of the considered options, Figure 4 summarises predicted indoor air temperatures during a week in July for the ground and top floors of the atrium. When a switching temperature of 20 °C was chosen for the thermotropic glazing, the average temperatures in the atrium decreased significantly, regardless of whether the optimistic or pessimistic values for the switched state were chosen. The non-switching solar control glazing with a low SHGC value of 20 % also had a clear positive effect. The results indicated that there is only a very marginal performance difference between the current glazing and the solar control glazing 66/34 if the 4th floor windows are opened. In the case of closed 4th floor windows, the current glazing actually outperforms the solar control glazing 66/34. The main reason why there seems to be so little difference between the current glazing and the alternative solar control glazing is related to the optical and thermal properties of these glazing systems. Although the solar control glazing 66/34 has a noticeably lower solar heat gain coefficient than the current glazing, it also has a much lower U-value. In other words, there will be lower solar gains but also smaller heat losses. The net result is a very similar outcome in terms of

[1] In reality other issues will probably have to be considered as well; e.g. thermotropic glazing in switched state is diffuse and will thus obscure the view from the atrium to outside, whereas the solar control glazing and the natural convection cooling do not have this side effect.

summer indoor temperatures. For most people this would appear counterintuitive in the first instance, illustrating the need to apply the sophisticated building simulation approach to find the appropriate solution to a complex problem.

5. CONCLUSION

Using a realistic case study as a common thread, this paper has demonstrated that:

- simulation can be used to predict the future performance of a building and thus allows the assessment of design alternatives which are being considered,
- simulation can be used to optimise the specifics of a product which is under development (i.e. the optimal switch temperature of thermotropic glazing), and that
- simulation can be used to improve our understanding of interactions in a complex integrated system such as a building.

In this particular case, neither strategy could have been assessed using traditional design methods. The first strategy is difficult to predict because of the atypical behaviour of the advanced glazing system. The second strategy is difficult to assess because of the strong coupling of heat and air flow which is very difficult to predict.

Several prediction results turned out to be counter-intuitive at first glance. An improvement over the current glazing can be achieved with non-switching solar control glazing only if an appropriate combination of U value and SHGC is chosen. Similarly, the performance of switchable glazing depends strongly on the use of a suitable control strategy. The air flows due to natural ventilation will be high during the night and relatively low during the day. The latter conclusion implies that night-time purge ventilation would be a promising low-energy cooling strategy. Such counterintuitive results would probably not have been achieved with traditional design methods, which tend to address issues in isolation.

Modelling and simulation, on the other hand, allows an integrated view of building structure, and other energy systems such as: people, heating, ventilation, air-conditioning, lighting, and outdoor climate. It is this capability, which makes computer modelling and simulation such a powerful tool for building design.

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