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Indoor environment quality in buildings and its impact on outdoor environment

Claude-Alain Roulet*

Solar Energy and Building Physics Research Laboratory, Swiss Federal Institute of Technology, CH 1015 Lausanne, Switzerland

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Abstract

The main purpose of buildings is to provide a comfortable living environment for their occupants. This includes, among others, thermal, visual and acoustic comfort as well as indoor air quality. Except during the 1950's and 1960's, it has always been considered important that an excess use of energy should be avoided in the construction and the management of a building, sometimes even at the cost of user comfort. Energy saving is, however, not the main purpose of the building. Indeed, if it were really so, the largest energy savings would be obtained by not erecting the building in the first place.

Since the Rio conference, there have been more and more incentives to save energy and lower the impact of buildings on the environment. Therefore, there is no excuse for the building sector not to adopt a sustainable development policy.

Some energy is required to control the indoor climate and indoor air quality. Therefore, it is often suspected that energy savings result in poorer indoor environment quality, or, on the contrary, that a high comfort level is the result of high technology and high energy consumption. This is not true. It is now generally admitted among building scientists that high quality energy services do not necessarily incur a high energy use, and that good environment quality can be obtained with a reasonable amount of energy and power, and with a low environmental impact.

The presentation brings some evidence from past and current research to support this assertion.

Keywords: Buildings; Energy; Environment; Comfort

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1. Introduction

1.1. Buildings and climate

Buildings are erected in most cases to protect the occupants from the external environment (extreme temperatures, wind, rain, noise, radiation, etc.), thus, providing a good indoor environment. A building that is well adapted to the climate protects its inhabitants against the extreme conditions observed outdoors, without creating uncomfortable internal conditions. According to Prof. Pierre Lavigne [1], the internal climate in a free floating building (that is without any heating or cooling system running) should be at least as comfortable as the outdoor climate. This strategy is explained below and in Fig. 1.

Depending on their clothing, occupants ask for different comfort temperatures in summer or in winter. Therefore, the comfort temperature zone is higher in summer than in winter [2].

A well-adapted building (curve A) has a good thermal insulation, appropriate passive solar gains (including movable and efficient shading systems), and adaptive ventilation devices. Therefore, it is protected against solar radiation in summer, but uses it to increase the internal temperature in winter. The result is a building which, in most temperate climates, provides comfort without other energy sources than the sun during most of the year. The energy use for heating is strongly reduced, as a result of a shorter heating season. Cooling is not required if the internal heat load stays within reasonable limits.

On the other hand, a poorly adapted building (curve B) is not that well insulated and is not designed for an efficient use of solar energy. Its free-floating internal temperature is then too low in winter and too high in summer. Expensive and energy consuming technical systems have to be installed to compensate for this misfit between the building and its surrounding climate. Such poorly adapted buildings are at the origin of the belief that a better comfort requires a larger energy use, since this is true for these buildings.

The EC research projects Joule PASSYS [3], PASCOOL [4], and OFFICE [5] provided advises and tools to design

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* Tel.: +41-21-6934557; fax: +41-21-6932722.
E-mail address: claude.roulet@epfl.ch (C.-A. Roulet).

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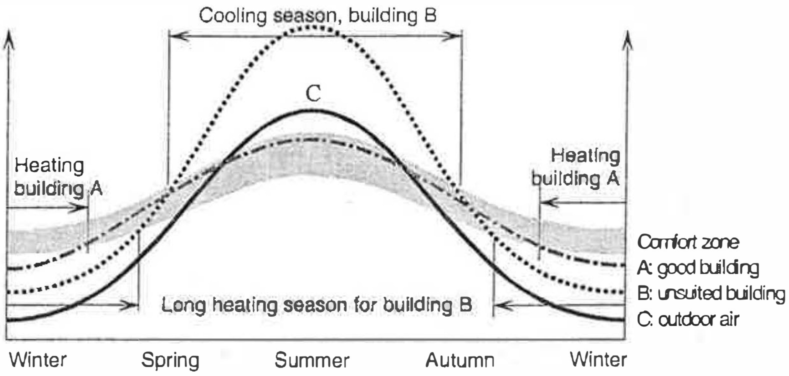

Fig. 1. Evolution of temperatures in a free floating building and its environment throughout the year (Northern hemisphere).

buildings that are comfortable and well adapted to the climate. The OFFICE project addressed retrofit of office buildings.

1.2. Energy and impact on outdoor environment

In tropical, temperate and cold climates, the largest impact of buildings on the outdoor environment during the whole life cycle results from energy used to ensure a comfortable indoor climate [6,7]. Therefore, we will limit our environmental considerations to the energy use of buildings.

Most energy surveys in buildings have shown a huge dispersion in the energy consumption, whatever this consumption is related to: building volume, heated floor area, envelope area, degree-days (Fig. 2), etc.

There are many reasons for this, most of them known: various levels of thermal insulation, heating and cooling system efficiencies, use of passive solar gains, inhabitant behaviour, ventilation rate, and, last but not least, building management.

1.3. Energy and well-being

Basically, buildings should be planned, built and managed to offer an environment in which occupants feel well. Loss of productivity and absenteeism will occur in a sick office building. Since a lost working hour costs as much as about 1000 kWh (enough to heat between 2 and 7 m^2 of office space for 1 year), the occupants' well-being should be considered as more important than the energy use in office buildings.

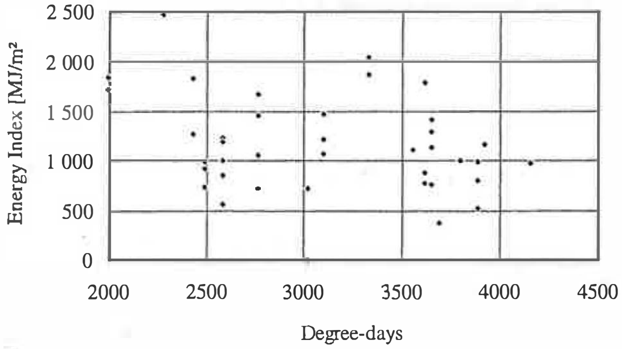

Fig. 2. Total energy index (energy index is the annual energy use divided by the gross heated floor area) and degree-days in 56 European office buildings. The largest energy consumption is more than six times the smallest [8]!

For this reason, managers are ready to invest in sophisticated HVAC equipment and to spend energy to ensure a good indoor climate. The results are very deceiving, as it was shown within the EC Joule European audit of indoor air quality in office buildings [9].

For example, Fig. 3 shows the energy index of 56 European office buildings in relation to a building symptom index (BSI)[1]. Obviously, large energy consumption does not result in better health. The correlation coefficient is 0.43 with a 95% probability to be between 0.05 and 0.70; there is a significant and positive correlation between the BSI and the energy index. On the average, the higher the energy consumption is, the larger are the number of building-related symptoms.

The link between these two variables could be common causes such as

- poor temperature control, or a lack of control of climate conditions, wastes energy and is not well accepted by occupants,
- air conditioning often uses much energy and is also often not well accepted by occupants, and
- well designed buildings should provide a very good indoor environment quality (hence a low BSI) together with a reasonable use of energy.

The facts presented in this introduction clearly show that if indoor environment quality and environmental impact are theoretically linked, it could be possible to provide an acceptable or even good indoor environment without an excess use of energy. Some evidence in favour of this affirmation is presented below.

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[1] This building symptom index (BSI) is the average number of symptoms occupants experienced during the past month, selected out of a list of 12.

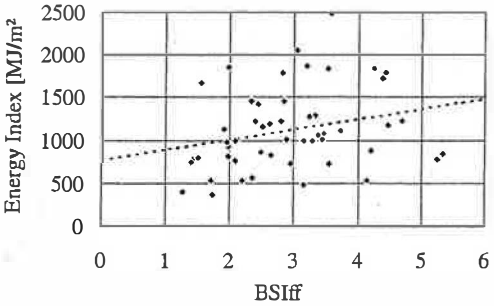

Fig. 3. Energy index related to the building symptom index (BSI) [8]. The BSI used here is the average number of building-related symptoms declared by the occupants, out of a list of 12.

2. Thermal isulation

It is well-known that a good thermal insulation reduces the energy consumption (and thus the impact on the environment) for heating as well as for cooling. There are several other advantages to it, that were forgotten during the energy wasting years (1960's and 1970's).

2.1. Impact of thermal insulation on thermal comfort

Perceived comfort temperature results from the energy balance of the body, which includes heat loss by convection and conduction to the surrounding air, by evaporation, and by radiation to and from neighbouring surfaces.

The internal surface temperature of the building envelope results from the heat balance on this surface. In steady state, it is given by

$$\theta_{si} = \theta_i - R_{si}U(\theta_i - \theta_e) \quad (1)$$

where θ stands for temperature, the suffix i being the internal temperature and e the external temperature, R_{si} the internal surface resistance (about 0.1 m^2 K/W) and U the thermal transmittance of the building envelope component.

In winter, the internal surface temperature is colder than the internal air temperature, the difference being largest when the building envelope component is poorly insulated (high U-value). The opposite is true in summer. The impact on the perceived comfort temperature close to external walls is not negligible when there is a large difference between outdoor and indoor temperature. For 20 K temperature difference and with 1 W/m^2 K U-value (common brick wall), it may decrease by 0.5 to 1 K, and it decreases by up to 3 K close to common double glazing (3 W/m^2 K U-value). In addition, air in contact with cold vertical surfaces may fall down, especially along large areas, and create cold drafts close to external walls.

The result of poor insulation is that space close to the external envelope cannot be used due to a lack of comfort, and that the internal air temperature is increased to compensate, without success in the worst cases, the effect of radiation of the body to cold surfaces.

2.2. Mould growth

In dwellings, an increase in mould growth is often observed after energy retrofitting measures were undertaken. It can indeed be expected that air humidity will be increased when

- single pane glazing is replaced by double pane glazing,
- old, untight windows and doors are replaced by new, airtight ones,
- ventilation openings are closed to avoid drafts, and
- the internal temperature is decreased in winter.

A necessary condition for mould growth is humid surfaces [10]. This happens when the internal surface temperature is close to the dew point of indoor air, that is either when the surface temperature is too low (poor thermal insulation) or when the indoor air is too humid.

In winter, single pane windows dry the internal air by condensation on the glass. The water freezes or drops on the shelf below the windows, the housewife wipes it from time to time, and the risk of mould growth is relatively low. Moreover, old single pane windows are often not very tight, and the ventilation rate remains high enough to avoid surface condensation on poorly insulated walls.

If the glazing is changed to more airtight and double pane windows, two phenomena occur at the same time: the ventilation rate may decrease, and condensation no more takes place on the glazing. Indoor air humidity is increased and surface moisture rises on cold surfaces — that is on poorly insulated walls — and mould grows.

From our experience, poor thermal insulation and thermal bridges are the primary cause of mould growth in Swiss dwellings, and probably also in many other countries. Buildings of the late 1060's were poorly insulated and not airtight; this results in an acceptable indoor environment if much energy is used to maintain a comfortable indoor temperature. But as soon as the indoor air dew point is increased or the ventilation rate is decreased, mould grows.

For such buildings, energy retrofit shall necessarily include a better thermal insulation, and then (or at the same time), improved air tightness. Today's thermal insulation standards would result, in most European countries, in an internal surface temperature higher than 2 K below internal temperature. This would allow for a relative indoor air humidity as high as 90% without surface condensation or 70% without mould growth. Such high indoor air humidity cannot be reached in dwellings with usual activity and minimum ventilation. In other words, if a dwelling is thermally insulated according to today's standards, lack of ventilation would result in unbearable odour and carbon dioxide concentration far before mould growth is possible. Mould growth after energy retrofit measures is the result of a poor planning of these measures, not the result of the measures themselves.

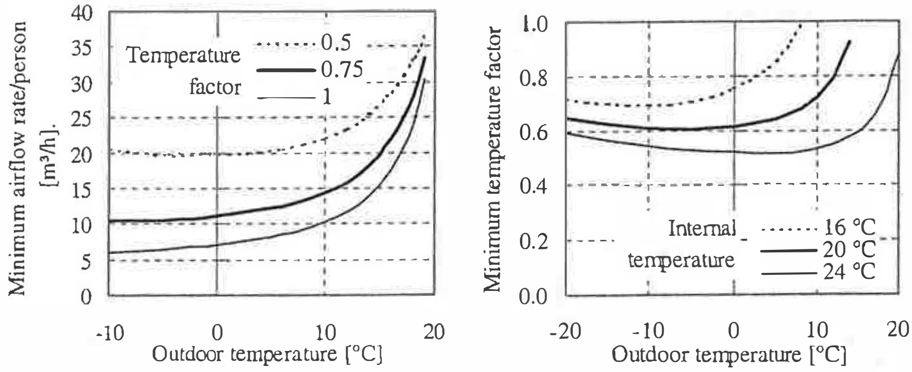

Fig. 4. Conditions to avoid mould growth on external walls (the simple model leading to these figures is given in Appendix A). Left: minimum airflow r per person, with internal temperature = 20°C. Right: minimum surface temperature factor, with 15 m^3/h airflow rate per person.

The ratio

$$f_{R_{si}} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \qquad (2)$$

is the internal surface temperature factor. In most European climates, this should at no place on the building envelope be smaller than 0.75, to avoid both discomfort and mould growth in cold season, at the minimum ventilation rates required for good indoor air quality. This ratio depends only on thermal insulation. It equals 1 for perfect insulation, and $1-R_{si}U$ on building envelope elements made of plane, homogeneous layers.

Another possibility is condensation or mould growth inside building elements. Important international collaboration allowed to provide various validated models as well as advises to assess and master this problem [11,12]. It also brought new knowledge on the conditions required for mould growth [10].

3. Airing and ventilation

3.1. Ventilation control

Contaminant and moisture concentration in indoor air depends on the intensity of contaminant and water vapour sources, and on the ventilation rate. Once the contaminant sources are limited to a minimum, the airing rate should be adjusted to limit contaminant concentration to acceptable levels.

A good example for the need for a controlled ventilation rate is shown in Fig. 4 left, which shows the minimum ventilation rate per person required to avoid mould growth in Swiss climates[2]. The ventilation rate can be reduced during the coldest season, while it should be strongly increased in mid-season. Uncontrolled infiltration through cracks and other leaks does exactly the opposite: the colder the outdoor temperature, the larger the infiltration rate. An airtigl envelope is a prerequisite for controlled ventilation. Ventil tion must be ensured by other means than infiltration: b either ventilation openings, stack effect ducts, mechanica or hybrid ventilation.

A controlled ventilation rate allows keeping the energ use for air heating or conditioning to a minimum whil ensuring at any time a good indoor air quality. Note th there is a strong interaction between thermal insulation an minimum ventilation rate to avoid mould or condensatio problems. Decreasing the temperature factor from 0.75 t 0.5 doubles the minimum ventilation rate on the coldes days.

Another interesting result shown in Fig. 4 (right): th lower the internal temperature, the better should be th thermal insulation to avoid mould growth. Common experience is just the opposite: poorly insulated rooms are ofter heated at lower temperature, and rooms planned to be heate at lower temperature are often less insulated.

3.2. Radon

A higher internal radon concentration is often feared when the ventilation rate is reduced to save energy. This is completely wrong, for several reasons.

First, when the radon concentration becomes unacceptable, it is one or more orders of magnitude too high. For example, in Switzerland, 10% of investigated buildings present a radon activity higher than 200 Bq/m^3, and a few up to 5000 Bq/m^3 [13], while outdoor air has an activity below 20 Bq/m^3. This means that indoor radon cannot be diluted through increased ventilation, since this would result in unacceptable draughts. The only way to avoid excessive radon activity is to keep it out of the building (airtight floor), or to blow it out before it enters the living areas (ventilated crawl space or cellar).

If the radon concentration is acceptable, decreasing the ventilation rate by as much as a factor of two would theoretically increase the radon concentration by the same factor, but this concentration would still be acceptable in many cases.

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[2] Additional ventilation may be necessary to eliminate water vapour from other sources than persons (cooking, laundry, etc.).

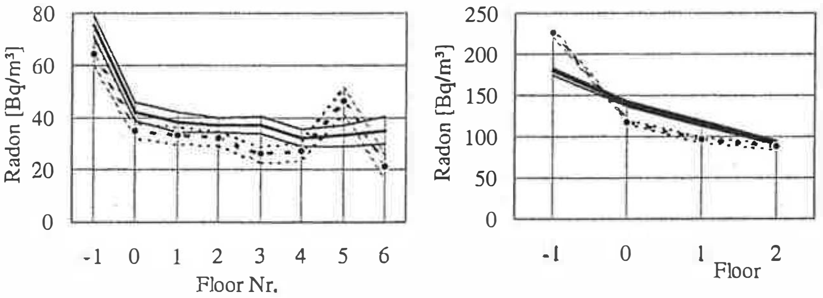

Fig. 5. Geometric average ±95% confidence interval of radon concentration in 25 multifamily dwellings (left) and seven single family homes (right) in Switzerland; before (full line) and after (dotted line) energy retrofit [14].

Moreover, there is experimental evidence that energy retrofit, including envelope air-tightness improvement, does not result in increased internal radon activity, but even decreases it slightly within the living area (Fig. 5). Radon activity was measured in 25 Swiss multifamily dwellings and seven single-family homes, before and after energy retrofitting, under very similar meteorological conditions [14]. On the average, the radon concentration increased slightly in the cellar, decreased on the lowest floor and remained about the same on the highest floor.

The reason is that radon enters the building through the cellar. If the envelope is more airtight, infiltration as well as exfiltration decrease. Controlled ventilation replaces uncontrolled infiltration, the part of outdoor air increases while the infiltration from the cellar decreases.

3.3. *Passive cooling*

Passive cooling through night-time ventilation is a comfortable, cheap, and energy-efficient way to keep the indoor environment within a comfortable temperature range in most European climates, in particular on the continent [4,15]. In well adapted buildings, it can ensure a comfortable indoor climate in summer without artificial cooling. Principles of passive cooling are

1. avoid internal heat load by promoting daylighting and low energy appliances,
2. avoid heat gains by using efficient shading systems (external and movable), and minimum ventilation rate during hot hours,
3. store the remaining heat gains in the building structure. For this, the heavy building structure should be in direct contact with the indoor environment,
4. cool the building structure with a large ventilation rate when the external temperature is lower than the internal temperature. Large ventilation rates are easily obtained by natural ventilation through windows and doors.

Such a strategy can be applied only in climates where the daily average outdoor temperature is within comfort limits, and where there is a significant temperature swing between night and day. This is fortunately the case in most European climates. In addition to the heavy structure, the building should have large and well-located openings, and these openings should be safe enough to remain open at night.

Fig. 6 shows the evolution of internal and external temperatures in two identical office spaces (40 m^3) of the LESO, which have been ventilated following two different strategies: (1) the usual strategy in office buildings, with ventilation during the day but not at night; and (2) the passive

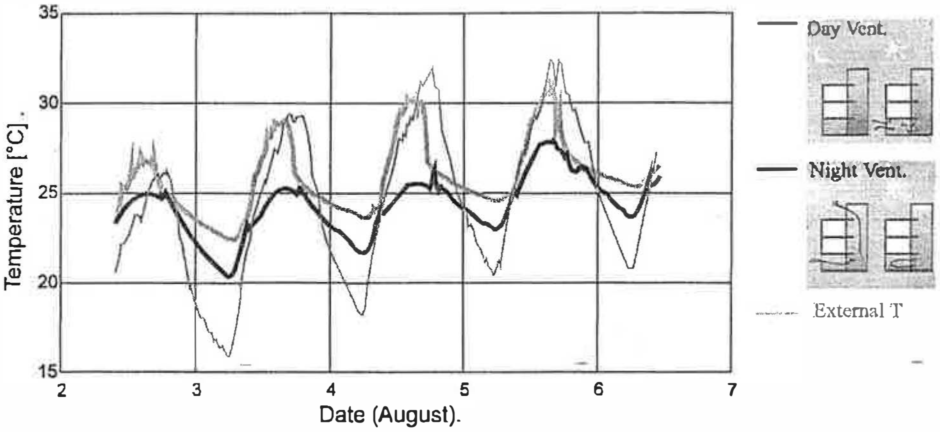

Fig. 6. Effect of passive cooling through night ventilation on the LESO building.

cooling strategy with natural ventilation at night. The office spaces have considerable thermal inertia and external solar blinds. The night ventilation rate corresponds to 10–12 air changes per hour. The office rooms are occupied by one person during 8 h per day, often with a personal computer running.

The experiment show that the peak indoor temperature can be decreased by up to 5° using the passive cooling strategy. This difference mainly results from large ventilation rate at night (between 5 and 10 ACH), and ventilation reduced to the hygienic minimum during the day. The airflow pattern is not the same in both strategy, and this may also influence the results, but as a secondary effect.

4. Boiler efficiency

There are several actions that can be undertaken to improve boiler efficiency, thus, decreasing the impact on the environment.

1. The boiler is the warmest place in the building, but often has a thinner thermal insulation than the building envelope. A good boiler thermal insulation limits the heat lost in the technical room.
2. Good tuning of the fuel-air mix of coal, fuel or gas boilers increases the boiler efficiency and decreases the emission of contaminants (soot, unburned fuel, carbon monoxide, etc.).
3. Periodical cleaning of fuel boilers removes the soot layer deposited on the heat exchanger. This layer insulates the heat exchanger, and a thick soot layer results in increased smoke temperature and poor efficiency. The time interval between cleanings can easily be checked by measuring the temperature of combustion gases: when it increases, it is time to clean the exchanger.

The global efficiency depends on the quality, the size, the adjustment, the control and the maintenance of the burner-boiler combination. It may be close to perfection, but can also be as low as 50%! In that situation, half of the fuel is lost and only contaminates the outdoor environment.

5. Temperature control

Proper control of the indoor temperature not only ensures a comfortable climate, but also avoids overheating and undercooling or worse, simultaneous heating and cooling. Sophisticated controllers exist now on the market and others are under development, that simulate and anticipate the thermal behaviour of the building. The result is a better comfort, together with significant energy savings for heating [16].

Even with simple controls, the set-point temperature should be adapted to the occupants' clothing and activity, that is, warmer in summer than in winter, and not the opposite!

6. Daylighting

The human eye had about a million years to adapt itself to daylight. It follows that daylighting provides better visual comfort than any other artificial lighting system. From the energy point of view, daylight does not use energy, and, at the same illuminance level, gives less internal gains than any other artificial lighting system. Daylighting, being as comfortable as environment-friendly, should be promoted as much as possible.

The efficiency of daylighting devices or systems can be measured by the reduction of the need of artificial lighting in a given internal environment. New devices, such as anidolic mirrors [17] can dramatically decrease the use of energy for lighting in office buildings or schools (Fig. 7).

7. Spatial arrangement

One architectural aspect that has a considerable impact on many social and technical issues is the choice between

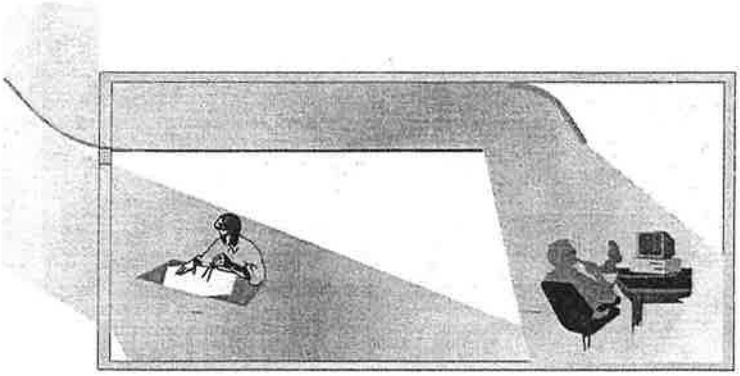

Fig. 7. Principle of the anidolic ceiling. A part of the light is reflected by carefully shaped mirrors to the back of the room.

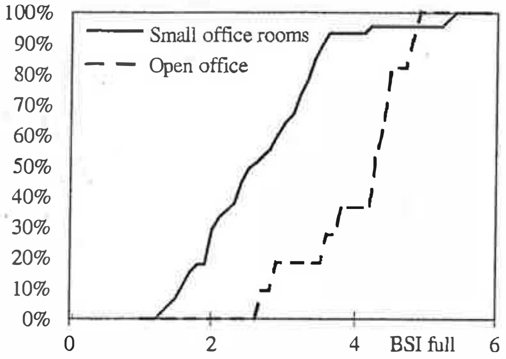

Fig. 8. Cumulated frequency distribution of the building symptom index in small office rooms and open offices.

small office rooms and open offices. Fig. 8, resulting from enquiries within the Joule II Indoor Air Quality Audit project, shows the significant difference in the number of sick building symptoms between these two types of offices.

It was also observed that several people who were more than 5 m away from a window considered that there was no window at their work place. This can be combined with another observation: occupants often complain when they cannot open a window, or more generally, when they have no influence on their environment (thermostat, lighting, etc.).

A straightforward conclusion is that planning should consider changing landscaped office rooms into small office rooms, and companies planning new office buildings should meditate this. It improves internal environment quality without any impact on the outdoor environment.

8. General environmental issues and interdisciplinarity

Architecture should adopt the sustainable development strategy: today's development should not hinder future development; and today's buildings and retrofits should not impede future developments. Energy saving is one of the issues only. Issues to be considered are, among others

- Prefer recycled and recyclable materials whenever possible.
- Avoid dangerous or damageable materials such as those containing CFC's or other halogenated compounds, formaldehyde, heavy metals, toxic organic solvents, etc.
- Use building techniques that allow deconstruction, making recycling easy, instead of demolition that generates mixed waste material.
- Consider the use of rain water collected on the roof for use in the toilets or other appliances that not require drinkable water.

Interdisciplinary work is paramount to improve both internal and external environments of buildings. This is well understood within most present research programmes addressing this topic.

Table 1
Functions of the building requiring energy, together with some ways to save energy and effects of these energy saving measures on comfort

Energy required for	Ways to save energy	Impact on indoor environment
Compensation of transmission heat loss in winter	Better, thicker insulation, low emissivity coated multiple glazing	Comfort improvement through higher internal surface temperature of envelope elements Improves health by preventing mould growth
Compensation of ventilation heat loss in winter	Lower ventilation rate	May result in low IAQ in "dirty" buildings
	Limit the ventilation rate to the required level	Less drafts, less noise, good IAQ
	Use heat exchangers	Limits the use of natural ventilation to mild seasons
Winter heating in general	Improve solar gains with larger, well placed windows Improve the use of gains by better insulation and good thermal inertia	If windows are poor: cold surfaces Over-heating if poor solar protections If well planned: nice visual contact with outdoor environment, very good summer and winter comfort
Elimination of heat gains during warm season	Use passive cooling	Very comfortable in appropriate climates and buildings
	Use efficient, well commissioned and maintained systems	Better IAQ and comfort
	Higher internal temperature	Should be kept within comfort zone
Internal temperature control	Comfortable set-point temperature, improved control	Avoid over- and under-heating
Air humidity control	Switch it off	No effect in many cases, but not applicable in hot and humid climates
Lighting	Use daylighting	Comfortable light, with limited heat gains when well controlled
	Use efficient artificial lighting	Comfort depends on the quality of light, limited heat gains

9. Conclusions

In buildings, energy is required, among others, for purposes given in Table 1. This table also proposes known ways to save energy, and presents some effects of these energy saving measures on comfort or indoor environment quality. It can readily be seen that there are many cases where energy conservation opportunities (ECOs), when well planned and executed, improve the indoor environment quality.

Of course, some ECOs may also destroy the indoor environment. The EU Directive 89/106 [18] considers good "hygiene, health and environment" as well as "energy economy and heat retention" as essential requirements. Measures such as low internal temperature or too low ventilation rate should, therefore, either be avoided, or taken only in case of emergency and for a limited period of time.

Some other ECOs should be used only in conjunction with others. A typical bad example is retrofitting windows in poorly insulated dwellings.

The following conclusions related to energy can be drawn from experience and surveys:

- Energy consumption varies strongly from building to building. In practice, it depends more on planning, construction, and management than on climate, building type or HVAC systems.
- It is, hence, possible to produce low-energy buildings with good indoor environment quality, pleasant architecture and various HVAC systems.
- If planning, construction, and management are performed by energy conscious persons, the result will be a low energy consumption with a good indoor environment quality.
- However, a single bad step (e.g. poor management or poor planning) may destroy the qualities of a building or the effects of a conscious management.

Healthy and comfortable buildings do not necessarily require much energy, and can have a limited impact on the environment. Smart managers, architects and engineers design, erect, and operate buildings in a way that both good indoor environment and low energy consumption can be achieved. By contrast, expensive measures to improve the indoor environment are sometimes counter productive; even when technical requirements (temperature, air flow rates, etc.) are met, occupants do not feel well.

Energy should not be saved at the cost of the indoor environment; this would result in a bad perception, and may generate unexpected waste.

Acknowledgements

Most of the knowledge presented here is extracted from the publications quoted below. I was lucky enough to collaborate with many of their authors, and I would like to thank all these experts for having greatly contributed to improving both internal and external environment quality. I will also apologise for having mentioned several facts that are well-known to many people, especially to the experts reading Energy and Buildings. They are nevertheless presented here for the sake of completeness. I also experienced that it is very useful to repeat them from time to time, until they are known to everybody.

Appendix A. Physical conditions for mould growth on building envelope elements

It is generally agreed that the risk for mould growth strongly increases when the water vapour pressure indoors is more than 80% of the saturation vapour pressure on cold surfaces [10]. The following formulas allow to assess this risk.

Internal surface temperature (°C):

$$\theta_{s,i} = \theta_e + f_{R_{si}}(\theta_i - \theta_e) \tag{A.1}$$

where θ is for the temperature (index i for internal and e for external environment), $f_{R_{si}}$ the internal surface temperature coefficient, which can be calculated at any location by solving the equation of heat.

Maximum internal water vapour pressure (Pa):

$$p_{i,\max} = 0.8 p_{\mathrm{sat}}(\theta_{s,i}) \tag{A.2}$$

External water vaopur pressure (Pa):

$$p_e = \varphi_e p_{\mathrm{sat}}(\theta_e) \tag{A.3}$$

where the external relative humidity (in %) is assumed vary linearly with the external temperature

$$\varphi_e = 75 - 0.25\theta_e \tag{A.4}$$

External moisture ratio (kg/kg):

$$x_e = \frac{M_w}{M_a}\frac{p_e}{p_a - p_e} = 0.62198 \times \left(\frac{p_e}{p_a - p_e}\right) \tag{A.5}$$

where M is for the molar mass (index w for water, a for air), p_a the atmospheric pressure.

Minimum airflow rate (m^3/h) for avoiding too high internal moisture:

$$\dot{V}_{\min} = \frac{S_{w,i}}{\rho_a(x_i - x_e)} \tag{A.6}$$

where $S_{w,i}$ is the generation of water vapour inside (kg/h), $\dot{V}$ the outdoor airflow rate (m^3/h), ρ_a the density of indoor air (kg/m^2).

The internal moisture ratio at a given airflow rate is obtained by solving the former equation

$$x_i = \frac{S_{w,i}}{\rho_a \dot{V}} + x_e \tag{A.7}$$

Internal water vapour pressure (Pa):

$$p_i = \frac{M_a p_a x_i}{M_a x_i + M_w} = \frac{p_a x_i}{x_i + 0.62198} \tag{A.8}$$

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