Energy efficiency and indoor air quality of seminar rooms in older buildings with and without mechanical ventilation

The present paper reports on an experimental study performed in a seminar room of the University of Luxembourg in a building of the 1970ies without a major renovation. This lecture room is typical for this building period and has a capacity of 60 seats. It is equipped with a mechanical ventilation system that is normally in operation on workdays for 11 hours a day in semester periods (8:00–19:00h), while windows can be opened manually. A blower-door test revealed that the room is not airtight. During a year, the ventilation system was shut “on” and “off” in periods of some weeks and the consumed final-energy was measured, as well as the indoor climate assessed by physical and psychological measurements. For instance, the measured CO₂ concentrations are marginally better with the ventilation system „on“, which was not perceived in any way by the occupants during the investigations. It was not possible to properly identify the impact of ventilation on the consumed heat-energy, as the room could not be thermally separated from the rest of the building. But with the system “on”, there was a clear increase in consumed primary energy due to the electric consumption of the fans. No relationship between the perceived percentage of dissatisfied and perceived climate could be observed. It is concluded that the typical normal operation modus is questionable for seminar rooms in older buildings with variable occupancy and that a simple shut down or semi-automatic user-controlled modus by low-cost retrofit seems advantageous.

Keywords: indoor climate; mechanical versus natural ventilation; thermal comfort; indoor air quality; PMV; PPD; seminar rooms in older buildings

1 Introduction

Many seminar rooms in schools, universities, and offices were and are equipped with mechanical ventilation systems, as humans are producing odors, water vapor, and CO₂, which have to be evacuated to assure good air quality, but only if the room is entirely occupied. With the increasing age of the buildings, the airtightness of the building itself and of the ducts are decreasing. Furthermore, the occupation rate of typical seminar rooms is strongly variable, i.e. changing from “empty” to “fully occupied”, while natural ventilation by opening windows is done on a large scale. Modern systems are controlled by sensors to adapt the volume flow rate to the needs in order to save energy. But in this case, priority has been given to older systems, about 50 years old, whose retrofit of this state-of-the-art technology is not economical or desirable. Those older systems are typically used in a time-controlled “on-off” modus with a fixed volume-flow of 100% or 0%. But as in addition natural ventilation by window opening is
possible and buildings become more and more leaky, analyzes were carried out through measurements and surveys on the impact of mechanical ventilation on air quality, indoor climate, and energy consumption. A literature review was also conducted and it was found that the studies did not focus on energy saving in comparison to natural and mechanical ventilation. Moreover, the studies were not performed for a typical older seminar room [1].

Therefore, energy meters for heat and electricity were installed to control the energy flow into the lecture room at the University of Luxembourg in the older building and several indoor climate parameters were measured to calculate the Predicted Mean Vote (PMV) according to Fanger [2] or ISO 7730. Finally, the occupants were asked about their perceptions of the room climate on a regular basis, while the ventilation system was switched “on” and “off” in time periods of some weeks during a complete year. This one-year-period was chosen to average seasonal influences and periods of lectures and holidays, i.e. to get a holistic view over one year to finally identify typical advantages and drawbacks of mechanical ventilation in seminar rooms with windows in older buildings.

A description of the classroom and measuring instruments is presented at the beginning, followed by the implementation and evaluation of the data. Then, the results are presented and discussed, before a summary and conclusions are formulated.

2 Description of the seminar room and the assessment methods

2.1 The room and its ventilation system

The seminar room entitled subsequently “C-02” is part of the University of Luxemburg on Campus Kirchberg, which was built in 1975 and has not yet undergone any important renovation. This lecture room is typical for this building, i.e. there are others of the same size and type. It has a capacity of 60 seats and a surface of 108 m² (12 m × 9 m) and is equipped with single glazed windows on one small side, which can be opened by the users. A photo of the room is shown in Fig. 1(a), while Fig. 1(b) shows a fresh air supply under the seats and an exhaust air outlet on the ceiling, i.e. a bottom-up piston-type ventilation is installed.

The incoming fresh air can be heated, humidified and even mixed with the exhaust air after a filtration, i.e. recirculation is technically possible in our system (Fig. 2). But neither recirculation nor humidification are used today, i.e. only preheating of supply air is done in winter using a coil fed by heating water with a maximum power of 63 kW. The system has two fans with a nominal volume flow of 4000 m³/h, while in the final installation with ducts and filters, several measurements were made on all seven outlets and a volume flow rate of \( V = 1740 \text{ m}^3/\text{h} \) or \( 29 \text{ m}^3/(\text{h} \cdot \text{person}) \) was found, corresponding to a typical value according to Roulet [3]. The two fans required together an average of \( P = 4.2 \text{ kW} \) leading to a Specific Fan Power of \( \text{SFP} = P/V = 2.4 \text{ Wh/m}^3 \), which obviously corresponds to a very high value [3].

Before the start of the experimental study, the airtightness of the seminar room was identified by two blower-door tests, while all doors and windows were closed, and the ventilation system was switched off. Once all air inlet and outlet openings are closed with thick plastic sheets and sealed around their circumference with adhesive tape. In this case, the test gave a value of \( n_{50} = 17 \text{ 1/h} \). In case these openings were not closed, a value of \( n_{50} = 20 \text{ 1/h} \) was measured. Both values demonstrate the lack of tightness in the seminar room. It was not possible to separate the part of the volume flow that exited to the outside of the building from the part of the volume flow that passed through the adjacent rooms inside the building. Therefore, it was concluded that there is inefficient ventilation in a non-aitight room. Nevertheless, this is not uncommon for this type of room and this construction period.

Fig. 1. Classroom C-02 of the University of Luxemburg (a); (b): ①: supply opening of fresh air, ②: return opening of exhaust air
Bild 1. Klassenzimmer C-02 der Universität Luxemburg (a); ①: Öffnung für Frischluftzufuhr, ②: Auslassöffnung Abluft

Fig. 2: Simplified schematic representation of the ventilation system
Bild 2. Vereinfachte schematische Darstellung der Lüftungsanlage
the indoor climate, a five-step scale was offered, whereby 1 represented "a complete dissatisfaction" and 5 "a total satisfaction". Requests for changes in temperature, air draft and the perception of light were recorded too, and for control reasons, also the gender and the nationality of the test persons.

In addition, three energy meters were installed to record the consumption of heat (one for the radiators and one for the coil in the ventilation system to preheat the supply air) and electricity used by the fans. Hence all energy flows into this room were measured, except for lighting, and except for uncontrollable air and heat flow from adjacent internal rooms. The weather data of Luxembourg were recorded too and later used to calculate the heating demand of this seminar room.

2.4 Analysis method

From the measured physical data, only the daily utilization time (8:00h–18:00h) were considered. The standard DIN EN ISO 7730 [6] was used to determine the PMV (Predicted Mean Vote) according to Fanger [2], with clothing assumed as 1.0 clo corresponding to normal winter office wear [7]. The physical activity was estimated to be 1 met for sedentary activity [7]. The satisfaction with the ventilation-situation and the desire for a change of the indoor climate was asked. The perception of the indoor climate and the noise situation was assessed by subjects on a seven-step scaling, whereby +3 was rated as "very good", 0 as "neutral" and −3 as "very bad". For the satisfaction with the indoor climate, a five-step scale was offered, whereby 1 represented "a complete dissatisfaction" and 5 "a total satisfaction". Requests for changes in temperature, air draft and the perception of light were recorded too, and for control reasons, also the gender and the nationality of the test persons.

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value increases up to 96.5%, as users open more often the windows. With the ventilation system “on” and “off”

3.2 Air temperature

Furthermore, the indoor air temperatures were registered and grouped into four intervals. The cumulated frequency diagrams (ref. to Fig. 5) are separated for winter and summer semester and for system “on” and “off”.

It is apparent that the ventilation system with the pre-heating of the supply air contributes significantly to the heating of this room, before all in the winter season. Without this preheating it is simply too cold (48% below 20 °C), which is also perceived by the users and detailed later. The heating system must normally be designed and adjusted in such a way that the heating system alone can deliver the necessary energy without the ventilation system and hence not depend on the preheating, i.e. it is a wrong design or adjustment, but not an advantage of the ventilation system as such. With system “on”, the air temperature is in winter during 88% between 20 and 24 °C, i.e. in a normal range.
outside and the higher air change rate. And in summer, the opposite happens. All measurements are therefore considered normal.

3.3 Relative air humidity

The relative indoor air humidity can be seen in Fig. 6. An acceptable relative humidity is between 30 and 60%, while humans are not very sensitive to this parameter [2]. In winter with the system „on“ the air is a bit dryer, which is a known effect and caused by the low absolute humidity.

3.4 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The Predicted Mean Vote (PMV) can be calculated according to Fanger [2] by using six different parameters: air temperature, radiation temperature, air speed, relative humidity, insulation level of clothing and physical activity of persons. A perfect comfort leads to PMV equal 0, while positive values signal that it is too hot and vice versa. If $-0.5 \leq PMV \leq 0.5$ the comfort is generally considered as “very good” and if $-1.0 \leq PMV \leq 1.0$ it is acceptable, as the number of dissatisfied people is below 20%. Table 1 shows the time-weighted averages of the calculated PMV during the lecture period in the winter and summer semester.

These PMV values state that it was slightly too cold, especially in winter with the ventilation system switched „off“, where the average PMV is below the threshold of $-0.5$.

### Table 1. Mean values for natural and mechanical ventilation per semester

|                                | PMV  |
|--------------------------------|------|
| Winter semester ventilation system switched on | -0.4 |
| Winter semester ventilation system switched off | -1.0 |
| Summer semester ventilation system switched on | -0.2 |
| Summer semester ventilation system switched off | -0.4 |
3.5 Physical quantities versus perceived comfort and climate

There were two surveys (see 6 Annex) per week during the winter semester, i.e. after two lectures per week, the students were interviewed in this lecture room C-02 after the respective course, in which a total of 83 persons took part. First, questions were asked about the perceived indoor air temperature (blue line) and we compared it to the measured one (red line, ref. to Fig. 9). Following the scaling of Fanger, we offered the students a range from $-3$ to $+3$ with $-3$ corresponding to “very cold”, 0 for “neither-nor”, $+3$ in case of “very warm”. It should be noted that the number of participants decreased during the semester from approximately 30 to 15 and that course two ended already after week 11.

Fig. 8 shows that with identical air temperatures the differences between system “on” and system “off” almost disappear and in all cases a very high satisfaction was reached.

Fig. 9. Averages of the perceived temperature compared to the measured average temperature during the lecture period (ref. to Fig. 7) are separated for winter and summer semester and for system “on” and “off”.

This figure illustrates a big difference between the system „on“ and „off“. In the latter case, the PPD is significantly higher, as only 47% are satisfied (PPD ≤ 20%). We assumed that this difference was due to the significant contribution of the ventilation system to the heating of the seminar room especially in winter, i.e. without the preheating of the supply air, it was simply too cold in the room. Therefore, the PPD was recalculated using the measured air temperatures from Fig. 5 with the ventilation system “on”, while the other parameters were used unchanged. This result is shown in Fig. 8.

Fig. 8. Cumulated frequency diagram of measured PPD values calculated with air temperatures of the system “on”, classified in 4 intervals and separated for summer and winter semester and ventilation system “on” and “off”.

Bild 8. Verteilungsdiagramm der gemessenen PPD-Werte, berechnet anhand der Lufttemperaturen, klassifiziert in 4 Intervalle und getrennt für Sommer- und Wintersemester und Lüftungsanlage „ein“ und „aus“.

Fig. 10. Averages of the perceived satisfaction with the room climate during the lecture period compared to measured PPD.

Bild 10. Mittelwerte der wahrgenommenen Zufriedenheit mit dem Raumklima während der Vorlesungszeit im Vergleich zu gemessenem PPD-Wert.
### Table 2. Measured heat and electric energies

|                     | Sept. | Oct. | Nov. | Dec. | Jan. | Febr. | March | April | May | Σ   |
|---------------------|-------|------|------|------|------|-------|-------|-------|-----|-----|
| Heat radiators [kWh/m²] | 0.8   | 1.0  | 3.1  | 3.6  | 6.7  | 9.0   | 5.8   | 1.3   | 0.1 | 31.4 |
| Heating coil [kWh/m²]    | 0.0   | 0.3  | 0.9  | 1.8  | 0.3  | 0.0   | 0.0   | 0.0   | 0.5 | 3.8 |
| Electric fans [kWh/m²]    | 2.9   | 2.9  | 2.1  | 1.5  | 0    | 0     | 4.0   | 5.0   | 3.8 | 22.2 |
| Σ [kWh/m²]               | 3.7   | 4.2  | 6.1  | 6.9  | 7.0  | 9.0   | 9.8   | 6.3   | 4.4 | 57.4 |

### 3.6 Energy consumptions

As already mentioned in paragraph 2.3, the final energy consumption for heating and ventilation of this room was measured by three installed meters, one heat meter for the radiators and a second one for the coil to preheat the supply air (Fig. 2). Finally, there was an electric meter to register the electric consumption of the two fans. All measured energies are summarized in subsequent Table 2.

For the sake of simplicity, we assumed that all electric energy is sooner or later transformed into heat and transferred to the room. This not fully correct, as the energy of the return fan of the exhaust air leaves the building (Fig. 2). But due to the simplification, we can add up and find a specific energy consumption characteristic of 57.4 kWh/m² for this seminar room, which is very low for such an old building [8]. Depending on the year, measurements in the years before for the whole complete building gave values between 200 to 250 kWh/m², which are typical for this category and this year of construction.

### 4 Discussion

First of all, it should be noted that a significant part of the room's heating energy is supplied by the supply air. Hence, turning off the mechanical ventilation requires adjusting the heating system, which is certainly possible, as otherwise, it is simply too cold (ref. to Fig. 5).

Regarding the quality of air, it can be concluded that mechanical ventilation improves it a bit (Fig. 4). The air is in general judged acceptable if CO₂ concentration is below 1000 ppm, which is achieved to 84.5% in winter and 98% in summer. The PPD below 20% is in all cases above 89% indicating satisfied users. It is only improved by a maximum of 4% by the mechanical ventilation system if the temperatures were identical (ref. to Fig. 8). These small differences based on our measured values, lead us to believe that climate measurements perceived by users cannot differentiate between the „on“ and „off“ system (ref. to Fig. 10).

As already mentioned, in winter, the indoor relative humidity is lower with the „on“ system as the ventilation rate is higher and the outdoor air is absolutely dry. In summer, the opposite occurs (ref. to Fig. 6). But we also know that people are generally not very sensitive to relative humidity, although the recommended range for good comfort is between 30% and 70% [2].

The true energetic consumption increase due to mechanical ventilation could not be measured in our study, as the seminar room could not be separated thermally from the rest of the building as the values in Table 2 clearly indicate. Therefore, it makes no sense to separate the „on“ and “off“ periods. But it is clear from Table 2 that this cost is above 22.2 kWh/m² of electric energy. Using Luxembourg’s conversion factor of 2.67 leads to an increase of 60 kWh/m² of primary energy for the electricity.

On top are the additional losses due to the additional volume flow of air V=1740 m³/h, even without heat recovery in our quite extreme case. Just to roughly estimate those losses, we divide by the surface of 108 m² and find 16 m³/(h·m²). Assuming an average temperature difference just for the winter semester between inside and outside of 17°C and of 15 weeks * 5 d/week * 11 h/d = 825 h we find:

\[
E_{\text{heat}} = \rho_{\text{air}} \cdot c_{\text{air}} \cdot 17 ^\circ C \cdot 16 \, \text{m}^3/(\text{h} \cdot \text{m}^2) = 76 \, \text{kWh/m}^2
\]

which can be converted with a factor of 1.1 (in case of fuel oil or gas in Luxembourg) to 84 kWh/m² of primary energy. We have to add both primary energies and find additional losses of 144 kWh/m², though a small part of it is available for heating purposes. Hence the increase of the specific primary energy characteristic is absolutely not negligible.

### 5 Conclusion

This study was done with the intention to assess purely experimentally the impact of mechanical ventilation in a typical seminar room of an approximately 50-year-old building. This analyzed room (C-02) can be considered as a typical room for university institutions during the same construction period without a major renovation. Three energy meters were installed, indoor comfort parameters were measured and a perceived ambient climate was
analyzed to determine the advantages and disadvantages of such a system.

The blower-door test revealed that the seminar room is not at all airtight due to the n\textsubscript{50} values of 17 l/h resp. 20 l/h. Technically, it would perhaps have been feasible with tracer-gas to separate which part of the test-volume air flow leaves towards the inside of the building and which part towards the outside. But in practice, the doors are not always closed and those tracer-gas measurements are complex in a large building.

Hence, we conclude that it is simply not possible to measure inside an older un-tight building one specific room, as this room cannot be separated from the rest. The single room is neither airtight towards other adjacent inner neighbouring rooms nor is it thermally insulated, i. e. there is a considerable heat transmission by conduction and convection.

In the measured characteristics of the indoor climate, small benefits with the ventilation system „on“ that are not perceived by users are detectable. The energy cost is very high, which could even be proven by our incomplete measures. The specific consumption of primary energy increases by about a third.

That is why in this type of old building, a simple shut down of the mechanical ventilation system is recommended for seminar rooms.

6 Annexe – Questionnaires

Your clothing

| Feet       |                  |                  |                  |                  |                  |
|------------|------------------|------------------|------------------|------------------|------------------|
| Socks      | ☐ no             | ☐ thin           | ☐ thick          | ☐ wool           |                  |
| Shoes      | ☐ no             | ☐ light          | ☐ outdoor        | ☐ winter-/ boots |                  |

| Underwear  | ☐ no             | ☐ short          | ☐ long           | ☐ heavy tissue   |                  |
| T-shirt    | ☐ no             | ☐ short sleeves  | ☐ long sleeves   | ☐ heavy tissue   |                  |
| Shirts/blouses | ☐ no        | ☐ shoulder free  | ☐ short sleeves  | ☐ long sleeves   |                  |

| Intermediate cloth. |                  |                  |                  |                  |                  |
| Intermed. cloth.    |                  |                  |                  |                  |                  |
| Underwear           | ☐ no             | ☐ short          | ☐ long           | ☐ heavy tissue   |                  |
| T-shirt             | ☐ no             | ☐ short sleeves  | ☐ long sleeves   | ☐ heavy tissue   |                  |
| Shirts/blouses      | ☐ no             | ☐ shoulder free  | ☐ short sleeves  | ☐ long sleeves   |                  |

| Outer clothing |                  |                  |                  |                  |                  |
| Pants          | ☐ no             |                  |                  |                  |                  |
| Dresses        | ☐ no             |                  |                  |                  |                  |
| Skirts         | ☐ no             | ☐ short          | ☐ long sleeves   | ☐ turtleneck     |                  |
| Pullovers      | ☐ no             | ☐ short sleeves  | ☐ long sleeves   | ☐ ankle length   |                  |
| Jackets        | ☐ no             |                  |                  |                  |                  |

How do you rate the indoor climate in this seminar room?

| 1) warm | 2) dry air | 3) fresh air | 4) uncomfortable temperature | 5) bright | 6) indoor climate overall good | 7) air quality overall good | 8) acoustics overall good | 9) no draft at all in the room | 10) no disturbing smell in the room | 11) I would like to turn off the ventilation system completely | 12) I am not satisfied at all with the indoor climate. | 13) The indoor climate is not important at all for me personally. |
|---------|------------|--------------|-----------------------------|-----------|--------------------------------|----------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------------|-----------------------------|--------------------------------|--------------------------------|

very | neither nor | very | cold | humid air | used air | comfortable temperature | indoor climate overall bad | air quality overall bad | acoustics overall bad | very strong draft | very disturbing smell | to turn on at max. power the ventilation system | very satisfied with the room climate. | the indoor climate is very important for me personally. |
I would like to have

|    | very much | neither nor | very much |
|----|-----------|-------------|-----------|
| 14 | the temperature colder | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | warmer |
| 15 | reduce draft | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | more draft |
| 16 | windows less open | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | windows more open |
| 17 | less light | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | more light |

How is your actual mental state, sensitivities?

|    | very good | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | very bad |

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