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Indoor Air Quality in energy-efficient buildings in Sweden: comparison with the Swedish residential housing stock and new conventional buildings

Sarka Langer[1,2,*], Despoina Teli[2,3], Lars Ekberg[4]

[1]IVL Swedish Environmental Research Institute, Göteborg, Sweden
[2]Chalmers University of Technology, Göteborg, Sweden
[3]Faculty of Engineering and the Environment, University of Southampton, UK
[4]CIT Energy Management, Göteborg, Sweden
[*]*Corresponding email: sarka.langer@ivl.se*

SUMMARY
The aim of this study was to compare the indoor air quality in newly built energy-efficient (passive) buildings in Sweden with the Swedish residential housing stock and new conventional buildings. We have used data from our previous publications to calculate Indoor Environmental Index (IEI), which is an average of Indoor Discomfort Index (IDI) that regards temperature and relative humidity, and Indoor Air Pollution Index (IAPI) that regards concentrations of indoor air pollutants. The passive building had significantly worse IEQ than the housing stock ($p < 0.05$). Further disentangling of the partial indexes revealed that the difference was almost entirely caused by low to very low relative humidity in the passive buildings which affected the IDI. It could be speculated that the low relative humidity is coupled to operation of the ventilation systems and air exchange rates. It might be of importance to review the ventilation requirements in the energy-efficient buildings.

KEYWORDS
Indoor Environmental Index; passive buildings; thermal comfort; indoor air pollutants; energy efficiency.

1 INTRODUCTION

The need of saving energy in buildings has led to the concept of low-energy buildings. According to Directive 2010/31/EU (EU directive 2010/31) all new buildings in the European Union should incorporate energy saving measures from the 1st of January 2021. Sweden's national energy goals have included a statement that energy use in the building sector is to be reduced by 20% by 2020 and 50% by 2050 (SOU 2008:110). The Swedish Building Code provides general guidelines for construction of buildings (BFS, 2011) and there are voluntary criteria for construction of low-energy buildings (FEBY, 2009). The rate of construction of low-energy buildings in Sweden has increased from 0.7% in 2008 to 10 % in 2013 (Wahlström et al., 2011; Norbäck and Wahlström 2016.). A type of very low-energy building that has become increasingly popular over recent years in Scandinavia is the 'Passive house', according to a voluntary building standard "Passivhaus standard". The majority of research on energy-efficient buildings has initially been focused on energy performance (*e.g.* Mahdavi and Doppelbauer, 2010), thermal comfort (*e.g.* Rohdin et al., 2014) or economic aspects (*e.g.* Audenaert et al., 2008). Energy efficient buildings are built to be well insulated and air-tight and the air exchange is ensured by mechanical ventilation systems with heat recovery (MVHR). Low energy use and good indoor air quality (IAQ) are sometimes considered incompatible.

Some examples of European studies on IAQ in low-energy buildings are given here. A field study in seven newly built energy-efficient buildings was performed in France (Derbez et al., 2014a). Indoor climate parameters, carbon dioxide, carbon monoxide, volatile organic compounds (VOC), aldehydes and $PM_{2.5}$ were measured before and during the buildings' first year of occupancy. Mechanical ventilation with heat recovery provided air exchange rates (AER) higher than 0.5 h^{-1} with the consequence of drier indoor air. A 3-year follow-up study in two of the energy efficient buildings showed no specific indoor air pollution or shortcomings in thermal comfort (Derbez et al., 2014). Another field study was conducted in 72 energy-efficient French dwellings with respect to IAQ and indoor climate. Most of the buildings were equipped with mechanical ventilation systems; the median AER was 0.4 h^{-1} and median relative humidity (RH) was 40 % (Derbez et al., 2017). IAQ and perceived thermal comfort were evaluated in six newly built energy-efficient homes in UK High levels of formaldehyde, increased RH and carbon dioxide suggested insufficient ventilation (McGill et al., 2015). An Austrian study (Wallner et al., 2015) constituted measurement of IAQ in 62 highly energy-efficient and 61 conventional buildings with regard to indoor climate and chemical pollutants. The energy efficient buildings were all equipped with mechanical ventilation while the conventional buildings relied on window opening for ventilation. The IAQ and indoor climate parameters were significantly better in the mechanically ventilated homes. Investigation of indoor air quality in Lithuanian low-energy residential buildings showed VOC concentrations at typical indoor levels; with elevated formaldehyde concentration. All the buildings had MVHR, the median AER was 0.2 h^{-1} and RH was in the range 40 – 60 % (Kauneliené et al., 2016).

Indoor environment was assessed in dwellings in 20 new passive buildings and 21 new conventionally built houses in Sweden during the 2012/2013 and 2013/2014 heating seasons The sample consisted of both single-family houses and apartments and the buildings were constructed between 2010 and 2013 (Langer et al., 2015). The measured parameters were temperature, RH, concentration of CO_2, NO_2, ozone, total volatile organic compounds (TVOC) and formaldehyde. All the buildings were equipped with MVHR; the median AERs were > 0.5 h^{-1} and the median RH was 30 % and 40 % in the passive and conventional buildings, respectively. A recent report (Langer et al., 2017) presents results from an investigation of IAQ in 10 apartments in a residential block built as passive house in 2015. The measured quantities were temperature, RH, ventilation air flows, concentration of CO_2, TVOC, NO_2, SO_2, ozone, formaldehyde and PM_{10} and $PM_{2.5}$. The results suggested that the air quality in the apartments was good compared to recommended guideline values for indoor air pollutants; the AERs were > 0.5 h^{-1}; indoor temperature was within the comfort zone and the RH was ~ 20 %.

Even if there is increasing knowledge on IAQ in energy-efficient buildings there is no simple way to compare the IAQ among these studies, given the magnitude of the individual measured parameters. In this article we intend to present an attempt to compare the IAQ in Swedish new energy-efficient buildings and new conventionally built houses with IAQ in the Swedish residential housing stock. The objective of this work is to find out whether the indoor environmental quality in the new buildings, passive and conventional, differs from the housing stock. For this, we use the concept of Indoor Environmental Index (IEI) which is a combination of Indoor Discomfort Index (IDI) and Indoor Air Pollution index (IAPI).

2 METHODS

Instead of comparing concentrations of single air pollutants in buildings it may be feasible to express them as a one single quantity. The concept of IAQ indexes enables a simplified quantification of the quite complex occurrence of individual compounds at varying concentrations. Attempts have also been made to create indexes combining the occurrence and concentrations of air pollutants with other indoor environmental factors, e.g. temperature. One such index – Indoor Environmental Index – has been proposed and demonstrated by Moschandreas and Sofuoglu (2004). The IEI (equation 1) is an arithmetic mean of Indoor Discomfort Index binding together temperature and relative humidity, and Indoor Air Pollution Index binding together gaseous (and particulate) air pollutants.

$$IEI = \frac{(\mathrm{IDI} + \mathrm{IAPI})}{2} \quad (1)$$

The IDI is calculated using the two indoor comfort variables, temperature and relative humidity, according to equation (2):

$$\mathrm{IDI} = \frac{1}{I}\sum_{i=1}^{I} 10 \, \frac{\lfloor CAopt - CAobs \rfloor}{CAucl - CAlcl} \quad (2)$$

where CA = comfort agent; opt = optimum value, T_{opt} = 22 °C, RH_{opt} = 45 %; obs = observed value; ucl = upper comfort level, lcl = lower comfort level,; I = 2.

The IAPI (equation 3) consists of a positioning term to place an observed value (C_{obs}) in a range of measured values, defined by minimum (C_{min}) and maximum (C_{max}), and a weighing term relating the observed value to a demarcation value (C_{dmc}) for a particulate air pollutant; J = 3. Demarcation values represent recommended guideline values for good indoor air quality.

$$\mathrm{IAPI} = \frac{1}{J}\sum_{j=1}^{J} 10 \left(1 - \frac{Cmax - Cobs}{Cmax - Cmin}\left(\frac{Cdmc - Cobs}{Cdmc}\right)\right) \quad (3)$$

The Swedish National Board of Housing, Building and Planning (Boverket) carried out a study on the technical status, energy use and indoor environment quality in the Swedish housing stock in the winter season of 2007/2008; the so called BETSI-study. Indoor climate parameters and AER were measured in almost 1 800 dwellings, built between 1800 and 2005, statistically selected to represent the residential housing stock. Measurements of indoor air pollutants NO_2, formaldehyde and TVOC were performed in a sub-sample consisting of 157 single-family houses and 148 apartments. The results from those 305 dwelling were evaluated and summarised (Langer end Bekö, 2013).

We have used the IEI concept (Moschandreas and Sofuoglu, 2004) and modified it to fit the data from the Swedish studies (Langer and Bekö, 2013; Langer et al., 2015; Langer et al., 2017). The air pollutants common in the investigations of the housing stock, the new conventional buildings and the new energy-efficient/passive buildings were NO_2, formaldehyde and TVOC, and the indoor climate parameters temperature and relative humidity.

The upper and lower comfort values used in equation (2) and the limit (demarcation) values used in equation (3) are summarized in Table 1. The concentrations of NO_2, formaldehyde and TVOC from the dwellings in the housing stock (n = 305) (Langer and Bekö, 2013) constituted the range (C_{min} and C_{max}) in the calculation of IAPI. The data for the conventional houses (n = 21) were from Langer et al. (2015) and the data for the passive houses (n = 30) were from Langer et al. (2015; 2017).

Table 1. Recommended guideline values for good indoor air quality used as ucl-, lcl- and dmc-values in the calculations of the indexes.

Parameter	Comfort or guideline value	Reference
Temperature	20 – 24 °C	FoHMFS, 2014
Relative humidity	30 – 60 %	ASHRAE, 2013
Nitrogen dioxide	40 μg/m^3	WHO, 2010
Formaldehyde	100 μg/m^3	WHO, 2010
TVOC	300 μg/m^3	UBA

The IEI is a unitless number which can achieve values between 0 (best IEQ) and 10 (worst IEQ). We have divided the index into bins separated by one (e.g. <0,1>, <1,2>, ..., <9,10>) and calculated frequency of the IEIs in the bins, for the three categories of housing. All data distributions were treated statistically to find if the differences between the samples were significant. Wilcoxon rank sum test for equal medians was used for the calculations

3 RESULTS AND DISCUSSION

Indoor Environmental Index

Figure 1 shows the frequency distributions of the Indoor Environmental Index in the bins for the housing stock, the conventional buildings and the passive buildings. The curves (Gaussian) are not intended to statistically fit the distributions but they help to illustrate graphically the differences in the frequency distributions.

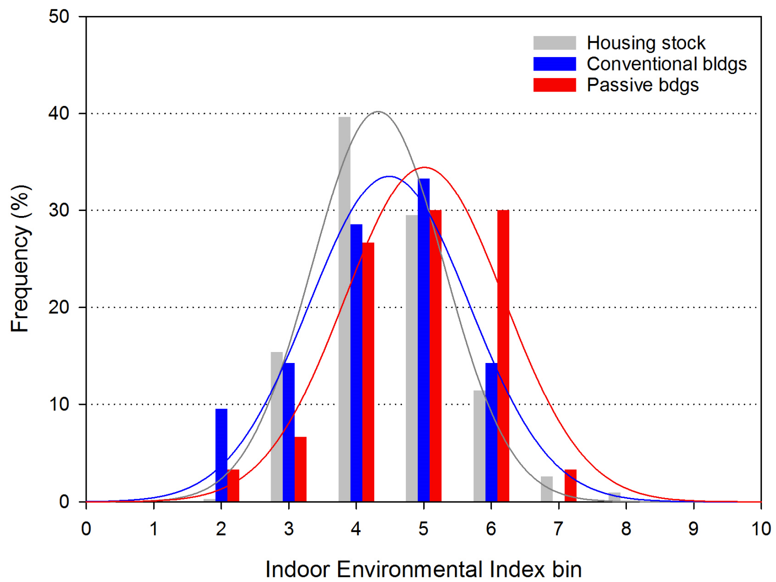


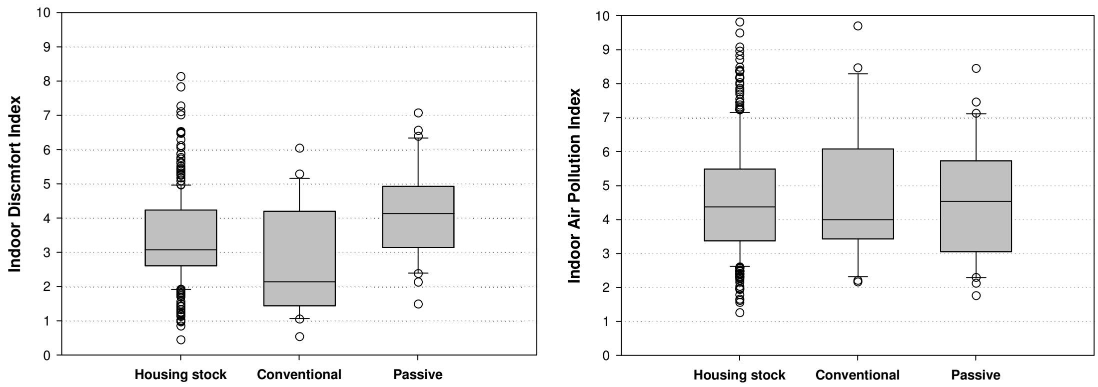
Figure 1. Frequency distribution of the IEI.

The results of the statistical comparison (Wilcoxon rank sum test) show a significant difference in the IEI between the housing stock and the passive buildings ($p = 0.0329$). The difference between the new conventional and passive buildings is also rather strong ($p = 0.0620$). The housing stock and the new conventional buildings are quite similar in terms of IEQ ($p = 0.5181$).

Indoor Discomfort Index and Indoor Air Pollution Index

In order to find out the contribution of the indoor climate and the levels of the air pollutants to the final IEI, we made comparisons of the three building categories with respect to IDIs and

IAPIs separately. Figure 2 presents the distribution of the IDI and IAPI, shown as box-plots, for the housing stock, the conventional buildings and the passive buildings. The bottom and the top of the boxes represent 25th and 75th percentiles and the band near the middle of the box is the median. The ends of the whiskers indicate 10th and 90th percentiles. The circles show the values for the best and the worst 10% of the populations.



a) b)

Figure 2. Boxplots showing the a) Indoor Discomfort Index, b) Indoor Air Pollution Index, for the housing stock (n=305), the new conventional houses (n=21) and the new passive houses (n=30).

The differences of the medians of the populations for IDI and IAPI were also tested for statistical significance. The p-values returned from the Wilcoxon rank sum test showed statistically significant differences between the IDIs of all three categories: housing stock vs. passive buildings p = 0.0038; housing stock vs. conventional buildings p = 0.0250; conventional vs. passive buildings p = 0.0027. The corresponding p-values for the IAPIs were 0.9535, 0.9905 and 0.8557.

Temperature and RH

Figures 3 and 4 show the distributions of the measured thermal parameters and their standard deviations. The measurements of the indoor climate parameters lasted for 14 days in the housing stock survey and for 7 days in the passive and new conventional buildings. Overall, mean dwelling temperatures fall well within the comfort zone set by the Indoor Discomfort Index in all three categories. The boxplots of standard deviations however illustrate differences, in particular between the conventional buildings and the other two categories. The difference means that the temperatures in new conventional buildings varied less during the measurement period. The temperature variation in the Swedish housing stock is significantly lower than in many other countries (Teli et al., 2018). Although thermal variation is not a variable currently considered in the Indoor Discomfort Index, recent research in the field of thermal comfort suggests that higher variation plays an important role for comfort and health (Van Marken Lichtenbelt et al., 2017).

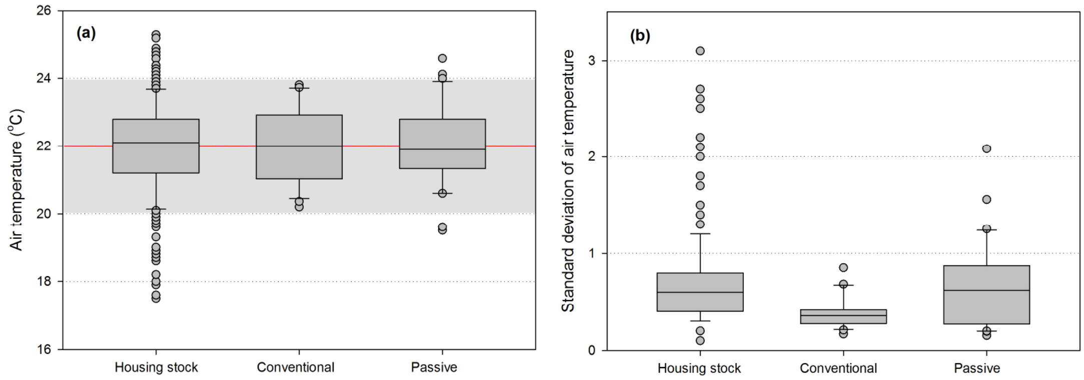


Figure 3. Boxplots showing the a) Air temperature, b) standard deviation of air temperature, for each of the three building categories. The shaded grey area indicates the temperature comfort zone; the line is the optimal temperature of 22 °C.

As can be seen in Figure 4, unlike temperature, mean relative humidity levels differ between categories while the variation of RH is quite similar. Whilst in the housing stock and new conventional buildings RH is most of the time within the comfort zone, in passive buildings it lies mostly below the lower limit of 30%. This explains the higher (worse) IEI index found in passive buildings and indicates that these buildings may be over-ventilated.

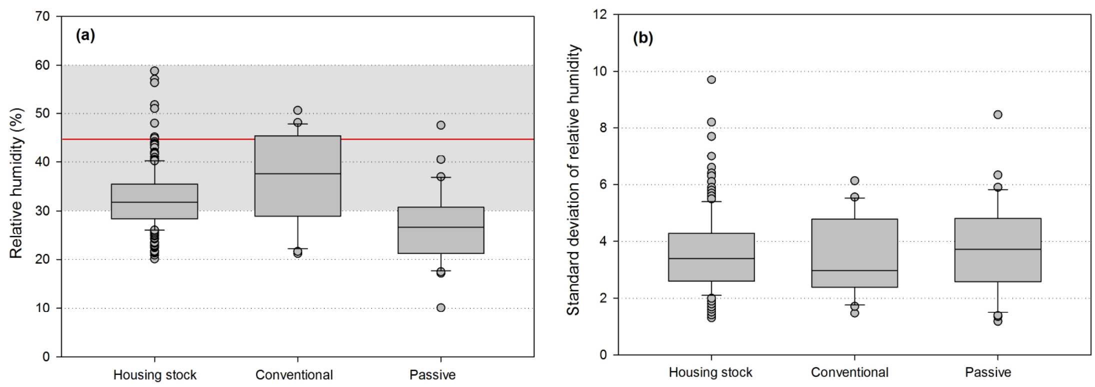


Figure 4. Boxplots showing the a) Relative humidity, b) standard deviation of relative humidity, for each of the three building categories. The shaded grey area indicates the RH comfort zone; the line is the optimal RH of 45 %.

The IEI provides an indication about the state of the indoor environment in the building categories (housing stock, new conventional buildings and passive buildings). However, it is important to analyse the partial indexes IDI and IAPI to understand what indoor air parameters contribute most to the differences. We have found in our previous studies that form the basis for this work that the levels of indoor air pollutants are mostly below the recommended guideline values. The IAPI indicates that the combined indoor air pollution in the building categories is quite similar. On the other hand, the differences in IDI are statistically strong and the indoor climate parameters explain the majority of the IEI.

We have investigated perception of the air quality in a sub-sample of the dwellings in passive buildings (Langer et al., 2017); there was no significant correlation between the measured RH and a feeling of dry air. However, the occupants rated the air as dry with a median score of ~2 on a scale between 0 (dry air) and 10 (humid air). The low RH might be associated with ventilation rate. A quick compilation of median RH and AER from the Swedish housing stock, the conventional and passive buildings, as well as the French (Derbez et al., 2014a; Derbez et al.,

2017) and the Lithuanian (Kaunelienė et al., 2016) buildings showed a clear negative correlation. Recent research has shown that the variations (standard deviations) in temperature affect comfort and health and as such, it should be considered together with the discomfort index.

4 CONCLUSIONS

We have demonstrated differences in indoor environments, expressed as Indoor Environmental Index, between three categories of housing in Sweden: the residential housing stock, new conventional buildings and passive buildings. The IEQ in the energy-efficient buildings was worse than in the other two categories. The difference was almost entirely caused by the RH; air in the passive buildings was too dry. We can speculate that the low RH is caused by ventilation rates. The results are not necessarily applicable to similar building categories operating in different climate conditions

There is still significant research required to ensure that IAQ is not sacrificed as a result of energy savings, for example that good IAQ is not traded for bad RH. Even if there was a large number of the data from the housing stock, the number of the new buildings was comparatively small. A larger, systematic survey on European or international level, with a well-prepared protocol, of measured and perceived IAQ together with building characteristics, energy demand, type and function of ventilation system and AER would be a good platform for acquiring sufficient amount of data. Such as a survey could be used for identification of solutions to low RH in passive houses and may initiate a fresh look at ventilation requirements in buildings.

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