Defining the metrics to assess the IAQ in low-energy residential buildings: results from IEA EBC

Annex 68 Subtask 1

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Indoor Air Pollutants

INFLUENCING FACTORS: Temperature, humidity, air velocity...

GOAL
To identify pollutants of interest for (low-energy) residential buildings
Pollution levels in residential buildings

• Objectives:
  – To provide an overview of the indoor pollutants and their concentration levels measured in residential buildings
  – To identify differences, if any, between the pollutants measured in buildings constructed using the standard building practice and the recent low-energy residential buildings

• Methodology:
  – To collect both peak and average concentration levels to distinguish long- and short-term exposure issues

• Notes:
  – The literature review has been limited to peer-reviewed articles and national research projects in the period from 2006 to 2016
  – The causes of good/bad air quality in residential buildings are not the purpose of this section and they are not discussed here.
Pollution levels in residential buildings

• Non low-energy residential buildings:
  – Cheng et al. (2010) for Australia,
  – Stranger et al. (2012) for Belgium,
  – Zhang et al. (2013), Du et al. (2014) and Liang et al. (2014) for China,
  – Guo et al. (2009) for China, Hong-Kong, Japan, Korea and Taiwan,
  – Kirchner et al. (2006) for France,
  – Park and Ikeda (2006), Azuma et al. (2007) for Japan,
  – Langer and Beko (2013) for Sweden, and
  – Logue et al. (2011) for USA – about 50% of exposure levels come from US non-low-energy buildings and 9% from low-energy buildings; the other data come from other industrialized countries (Canada, Germany, France Spain, UK, Denmark, Finland, Japan, Hong-Kong, South Korea...).

• Low-energy residential buildings:
  – Cheng et al. (2010) for Australia,
  – Stranger et al. (2012) for Belgium,
  – Du et al. (2014) for China,
  – Derbez et al. (2015) for France,
  – Park and Ikeda (2006) for Japan, and
  – Logue et al. (2011) for USA.
Pollution levels in residential buildings

Concentration (µg/m³)

1.4-Dichlorobenzene
Acetaldehyde
alpha-Pinene
Benzene
Carbon monoxide
Chloroform
Decane
d-Limonene
Dodecane
Ethylbenzene
Formaldehyde
Hexanal
Hexane
Naphthalene
Nitrogen dioxide
PM10
PM2.5
Styrene
Toluene
Tetrachloroethylene
Trichloroethylene
TVOC
Xylene
Exposure Limit Values

Exposure Limit Values (ELV)
Long-term (Chronic) and Short-term (Acute) exposures

Epidemiological studies

Animal experiments
(Toxicity Reference Values - TRV)

Indoor Air Guideline Value (IAGV)
- World: GV – WHO
- EU: GV – INDEX
- France: VGAI (Valeurs Guide de l’Air Intérieur) – ANSES
- Germany: RW (Richtwerte) – UBA
- Netherlands: TCA (Tolerable Concentration in Air) – RIVM
- USA: NAAQS (National Ambient Air Quality Standards) – USEPA
- Canada: RIAQG (Residential IAQ Guideline) – Health Canada
- California (USA): REL (Reference Exposure Levels) – OEHHA
- ...

Occupational Exposure Limits (OEL)
- World: TLV (Threshold Limit Values)
- EU: IOELV (Indicative Occupational Exposure Limit Values) and BOELV (Binding Occupational Exposure Limit Values)
- France, Beligique: VLEP (Valeurs Limites d’Exposition Professionnelle)
- Germany: AGW (Arbeitsplatzgrenzwert)
- Denmark: GV (Grænseværdier for luftforurening)
- Netherlands: OEL (Occupational Exposure Limits)
- Poland: MAC (Maximum Admissible Concentrations)
- Spain: VLA (Valores Limite Ambientales)
- UK: WEL (Workplace Exposure Limit)
- USA, Canada: TLV (Threshold Limit Values)
- California (USA): PEL (Permissible Exposure Limit)
- ...

Lowest Concentration of Interest (LCI)
- World: none
- EU: EU-LCI – DG JRC
- France: CLI (Concentration Limite d’intérêt) – ANSES
- Germany: NIK (Niedrigste Interessierende Konzentration) – AgBB
- ...

- Factor 10: more sensitive population.
- Factor 10: longer exposure duration.
- Factor 10: for suspected carcinogens.
- Proven carcinogens not to be emitted.
Exposure Limit Values

- ELV database:
  - World Health Organization, Europe, Austria, Belgium, USA – California, Canada, China, France, Germany, Hong-Kong, Japan, Korea, Portugal and United Kingdom (UK)
List of pollutants of concern for Annex 68

• Methodology:
  – For each pollutant, all data compiled previously was used to calculate **annual or maximum** minimum, 1\textsuperscript{st} quartile, median, 3\textsuperscript{rd} quartile, maximum and average concentrations of pollutants,
  
  – For each pollutant, the **minimum value** of available **ELVs** for **long-term or short-term exposure** was used,
  
  – 3\textsuperscript{rd} quartile (75\% percentile) concentration was compared with ELV. Pollutants with ratios higher than 0.1 were kept and considered to be pollutants with potential risk for health and relevant to Annex 68 (low-energy buildings).
List of pollutants of concern for Annex68

- Illustration for long-term exposure

**Low-energy buildings**

- Benzene
- Formaldehyde
- Trichloroethylene
- PM2.5
- PM10
- Styrene
- Nitrogen dioxide
- alpha-Pinene
- Acetaldehyde
- Radon
- Naphthalene
- Toluene
- Xylene
- Tetrachloroethylene
- Chloroform

+ pollutants according to previous studies on pollutant prioritization (WHO, INDEX, ...)

[Graph showing annual average concentration/long-term ELV for various pollutants in low-energy buildings]
<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Long-term Exposure</th>
<th>Short-term Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ELV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Acetaldehyde</strong></td>
<td>48</td>
<td>Japan</td>
</tr>
<tr>
<td><strong>Acrolein</strong></td>
<td>0.35</td>
<td>USA-California</td>
</tr>
<tr>
<td><strong>α-pinene</strong></td>
<td>200</td>
<td>Germany</td>
</tr>
<tr>
<td><strong>Benzene</strong></td>
<td>0.2</td>
<td>France</td>
</tr>
<tr>
<td><strong>Carbon dioxide</strong></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Formaldehyde</strong></td>
<td>9</td>
<td>USA-California</td>
</tr>
<tr>
<td><strong>Naphthalene</strong></td>
<td>2</td>
<td>Germany</td>
</tr>
<tr>
<td><strong>Nitrogen dioxide</strong></td>
<td>20</td>
<td>France, Canada</td>
</tr>
<tr>
<td><strong>PM10</strong></td>
<td>20</td>
<td>WHO</td>
</tr>
<tr>
<td><strong>PM2.5</strong></td>
<td>10</td>
<td>WHO</td>
</tr>
<tr>
<td><strong>Radon</strong></td>
<td>200</td>
<td>Austria, Canada, Hong-Kong</td>
</tr>
<tr>
<td><strong>Styrene</strong></td>
<td>30</td>
<td>Germany</td>
</tr>
<tr>
<td><strong>Toluene</strong></td>
<td>250</td>
<td>Portugal</td>
</tr>
<tr>
<td><strong>Trichloroethylene</strong></td>
<td>2</td>
<td>France</td>
</tr>
<tr>
<td><strong>TVOC</strong></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Mold</strong></td>
<td>200</td>
<td>EU</td>
</tr>
</tbody>
</table>
IAQ indices: the problematic

Step 1: Sub-indices

- \( I_i = \frac{C_i}{ELV_i} \)
- \( I_i = f_i(C_i) \) or \( f_i\left(\frac{C_i}{ELV_i}\right) \)

| Grade for PM\textsubscript{10} (µg/m\textsuperscript{3}, 24h) - Chiang and Lai (2002) |
|-----------------|-------|-------|-------|-------|-------|-------|
| Grade | 20 | 40 | 60 | 80 | 100 |
| C\textsubscript{i} | >350\geq | X | >150\geq | >50\geq | >25\geq |
**IAQ indices: the problematic**

**Step 2: Aggregation of Sub-indices**

- **Weighted Additive Form**

- **Root-Sum-Power Form (non-linear aggregation form)**

- **Root-Mean-Square Form**

- **Max Operator**
IAQ indices: the problematic

Aggregation limitations (Sharma and Bhattacharya, 2012):

- **Ambiguity**
  \[ I = I_1 + I_2 \]

- **Eclipsing**
  \[ I = \frac{1}{2} (I_1 + I_2) \]

Non-ambiguous and non-eclipsing aggregation = \text{Max} (sub-indices)
IAQ indices from literature  
*(based on Kirchner, Jédor and Mandin, 2006)*

**Max. operator**

Cohas (1996)  
any pollutant

\[
I_{BILGA} = \begin{cases} 
\max \left( \frac{C_{i}^{\text{obs}} - ELV_{c,i}}{ELV_{a,i} - ELV_{c,i}} \right) & \text{if } C_{i}^{\text{obs}} > ELV_{c,i} \\
\max \left( \frac{C_{i}^{\text{obs}} - ELV_{c,i}}{ELV_{c,i}} \right) & \text{if } C_{i}^{\text{obs}} \leq ELV_{c,i}
\end{cases}
\]

**Weighted Additive Form**

Gadeau (1996)  
CO, CO₂, NO₂, HCHO

Castanet (1998)  
CO, CO₂, Bacteria

Chiang and Lai (2002)  
CO, CO₂, HCHO, TVOC, PM₁₀

QUAD-BBC (2012)  
CO₂, NO₂, SO₂, O₃, CO, HCHO, Acetaldehyde, Ethylbenzene, Styrene, Toluene, o-Xylene, Acetone, PM₂.₅, PM₁₀

Sofuoglu and Moschandreas (2003)  
Formaldehyde, TVOC, CO, CO₂, PM₂.₅, PM₁₀, Fungi, Bacteria

\[
I_{CLM2000} = \frac{1}{4} \left( \frac{[CO]}{30} + \frac{[CO_2]}{4500} + \frac{[NO_2]}{0.4} + \frac{[HCHO]}{0.06} \right)
\]

\[
I_{LHVP} = \frac{[CO]}{5} + \frac{[CO_2]}{1000} + \frac{[Bacteria]}{1000}
\]

\[
I_{IEI_{IAQ}} = \frac{1}{p} \sum_{i=1}^{p} \text{Grade}_i
\]

\[
I_{QUAD-BBC} = \sum_{i=1}^{p} \frac{C_{i}^{\text{obs}}}{ELV_i}
\]

\[
I_{IAPI} = \frac{1}{8} \sum_{i=1}^{8} 10 \times \left[ 1 - \frac{C_{i}^{\text{max}} - C_{i}^{\text{obs}}}{C_{i}^{\text{max}} - C_{i}^{\text{min}}} \left( \frac{ELV_{c,i} - C_{i}^{\text{obs}}}{ELV_{c,i}} \right) \right]
\]
The DALY approach
(Logue et al., 2011)

Disability-Adjusted Life-Years (DALY):

WHO definition: One DALY can be thought of as one lost year of "healthy" life. The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability.

\[ \text{DALY}_{\text{disease}} = \text{YLL}_{\text{disease}} + \text{YLD}_{\text{disease}} \]

\(\text{YLL}_{\text{disease}}\): Years of Life Lost due to premature death from the disease,
\(\text{YLD}_{\text{disease}}\): Years of Life Disability, weighted from 0 to 1 depending on disease severity.
The DALY approach – Calculation
(Logue et al., 2011)

• **Intake-Incidence-DALY method:**

  Epidemiology based concentration-response (CR) functions to quantify disease incidence rates + estimates of DALYs per disease incidence reported in the literature.

  $$DALY = \frac{\partial DALY}{\partial \text{disease incidence}} \times \text{disease incidence} = \frac{\partial DALY}{\partial \text{disease incidence}} \times \text{pop} \times y_0 \times (1 - e^{-\beta \times 0.7 \times C_i})$$

  $\text{pop}$: number of persons exposed (usually 100,000),
  $y_0$: baseline prevalence of illness per year,
  $\beta$: coefficient of the concentration change (natural logarithm of the relative risk divided by the change in mean/median exposure),
  $C_i$: exposure-related concentration ($\mu g/m^3$),
  Pollutants: **PM2.5, CO, NO2, SO2, O3**

• **Intake-DALY approach:**

  Used the work of Huijbregts et al. (2005) to calculate the health impact associated with intake of pollutants based on animal toxicity literature.

  $$DALY = \frac{\partial DALY}{\partial \text{intake}} \times \text{intake} = \left[ \left( \frac{\partial DALY}{\partial \text{intake}} \right)_{\text{cancer}} \times ADAF + \left( \frac{\partial DALY}{\partial \text{intake}} \right)_{\text{non-cancer}} \right] \times [Q_{\text{intake}} \times C_i \times \Delta t]$$

  $ADAFA$: Age-Dependent Adjustment Factor (-),
  $Q_{\text{intake}}$: volume rate of air intake ($m^3$/day),
  $\Delta t$: considered period of time (day, usually 365),
  $C_i$: exposure-related concentration ($\mu g/m^3$).
Metrics for Annex68

• IAQ:
  – Sub-indices per pollutant
    • Long-term exposure:
      – ELV-based approach: simple detection of the potential risks that is easy to comprehend by designers i.e. “to stay below the ELV level for each pollutant!”
      – DALY approach: effects on health, tool for decision makers, “which efforts should be made and for which pollutants to achieve the largest effects on the population health”
    • Short-term exposure:
      – ELV-based approach: frequency of exceedance of ELV over the occupation period

  – Indices = max(ELV sub-indices) and = sum(DALY sub-indices)

• Energy:
  – Primary energy consumption of the building
Metrics for Annex68 – Dashboard

Long-term effects

ELV indices

DALY

Maximal value: 8.5 – Pollutant: BENZENE

Total: 1166 DALYs lost/(year.100,000 persons)

Short-term effects

ELV indices

Energy Consumption

Maximal value: 55% – Pollutant: PM2.5

Energy consumption: 130 kWh_{pe}/m^2.year

Data represented here are just for display and do not represent actual situation
Conclusions

• Pollutants of interest:
  – List of 16 pollutants: acetaldehyde, acrolein, $\alpha$-pinene, benzene, carbon
dioxide, formaldehyde, naphthalene, nitrogen dioxide, PM10, PM2.5, radon,
styrene, toluene, trichloroethylene, TVOC and mold.

• Quantification of IAQ:
  – ELV-based approach for both long- and short-term exposure
  – DALY approach for long-term exposure

• Use of Annex68 metrics: to evaluate solutions for a better IAQ in low-
energy residential buildings
  – ELV-based approach: % of reduction of the max related to variation of
$kWh_{PE}/m^2\cdot year$
  – DALY approach: % of reduction of the total DALY related to variation of
$kWh_{PE}/m^2\cdot year$
Thank you