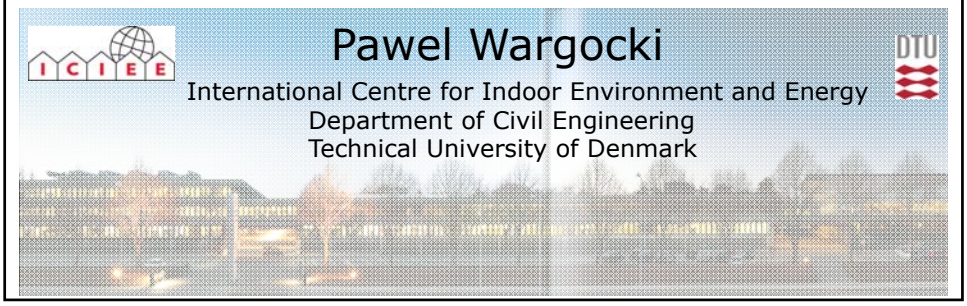
On The Quest For Indices Defining Indoor Air Quality. What Is A Reasonable Approach?



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Objectives

- Review the main indices and approaches used so far to characterize and define indoor air quality
- Understand pros and cons of different indices used to define indoor air quality
- Discuss the potential strategies for setting an index of indoor air quality
- Define necessary research priorities

Indoor air quality definitions

- EPA and Wikipedia: Indoor Air Quality (IAQ) refers to the air quality **within and around buildings and structures**, especially as it relates to the **health and comfort of building occupants**.
- WHO: The quality of air inside homes, offices, schools, day care centers, public buildings, health care facilities or other private and public buildings where people spend a large part of their life is an essential determinant of **healthy life and people's well-being**.
- OECD: Indoor air pollution refers to **chemical, biological and physical contamination** of indoor air. It may result in **adverse health effects**.
- Glossary (ISIAQ): Air quality: An indicator of the **types and amounts of pollutants** in the air that might cause **discomfort or risk of adverse effects on** human or animal **health,** or damage to vegetation.
- ASHRAE (in the context of ventilation): air in which there are **no known contaminants at harmful concentrations** as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express **dissatisfaction**

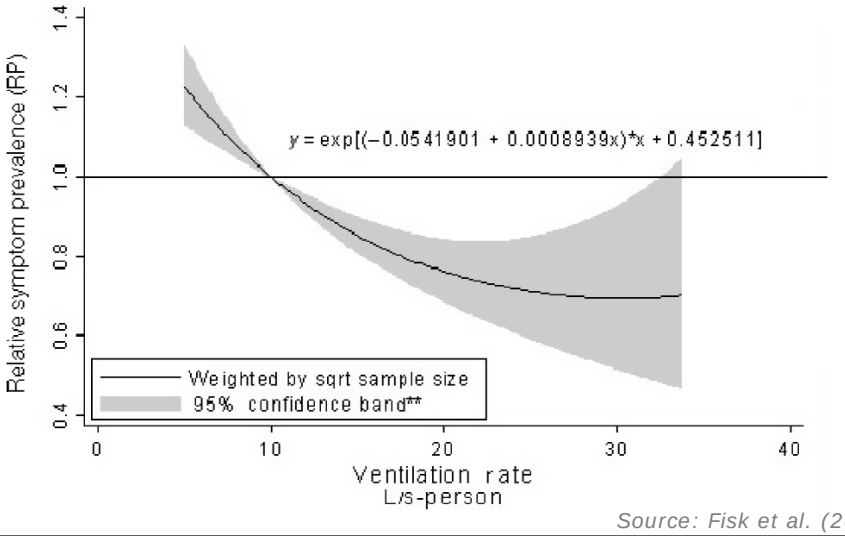
Health definitions

- WHO: Health is a **state of complete physical, mental and social well-being** and not merely the absence of disease or infirmity
- Merriam Webster's Dictionary: The condition of being sound in body, mind, or spirit, esp. **freedom from physical disease or pain**
- American Thoracic Society: An adverse health effect of air pollution is constituted by **any of these**: biomarker response, decreased (health-related) quality of life, permanent detectable adverse physiological impact, symptoms associated with diminished quality of life or change in clinical status, detectable effects on clinical measures, effects on mortality, increased risk of health even in the absence of frank illness

Overview of the most often used indices

- "Ventilation rate"
- Carbon dioxide (CO_2) [CO_2 => Ventilation rate]
- Total concentration of volatile organic compounds (TVOCs)
- Acceptability of (or the percentage of dissatisfied with) indoor air quality
- Occupant complaints (satisfaction) and acute health symptoms prevalence

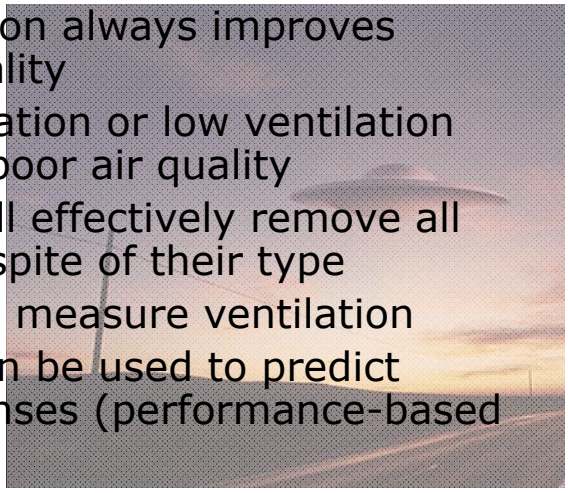
Ventilation IAQ, health & performance



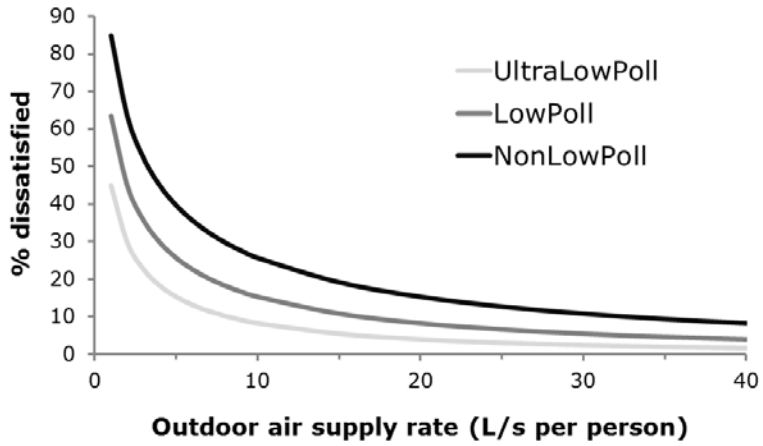
Source: Fisk et al. (2009)

Common beliefs and misconceptions

- More ventilation always improves indoor air quality
- Lack of ventilation or low ventilation rates means poor air quality
- Ventilation will effectively remove all pollutants in spite of their type
- It is simple to measure ventilation
- Ventilation can be used to predict human responses (performance-based metric)

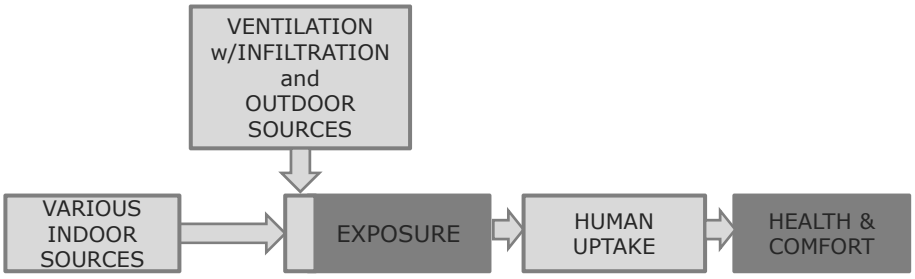


Ventilation requirements @various pollution load

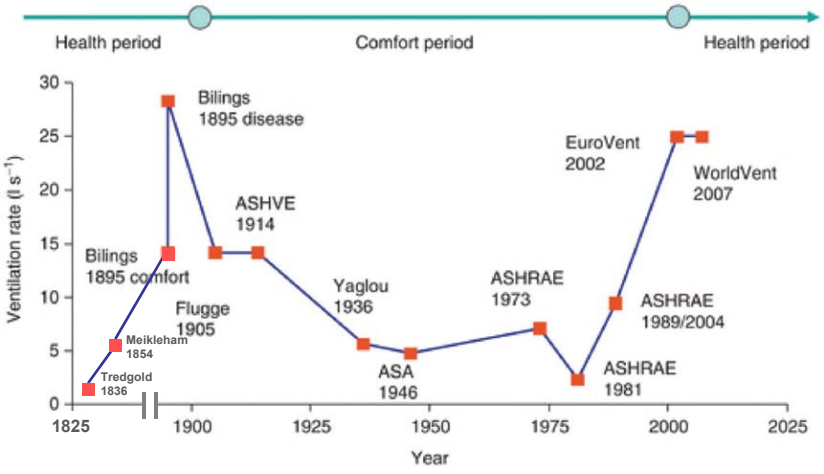


Source: EN15251 (2007)

Ventilation is merely an intermediate index rather than causative factor



Ventilation requirements through history

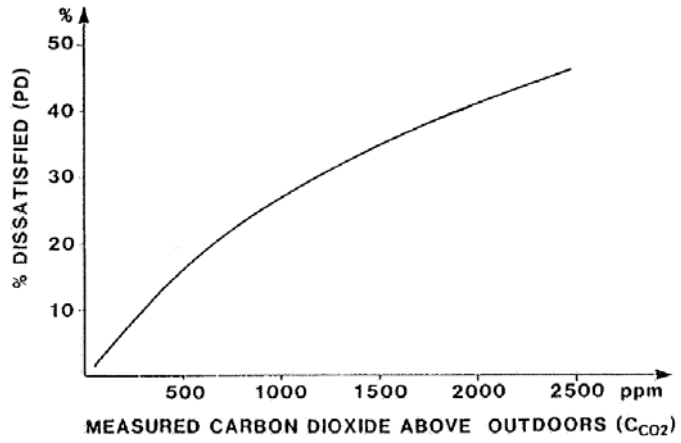


Adapted from Li (2013)

Intermediate conclusion, ventilation

- Although simple, relatively easy to verify and readily available ventilation rate, as is used today, although it does sometimes show association with IAQ and human outcomes it may not be considered as a solid and credible metric for predicting indoor air quality between buildings

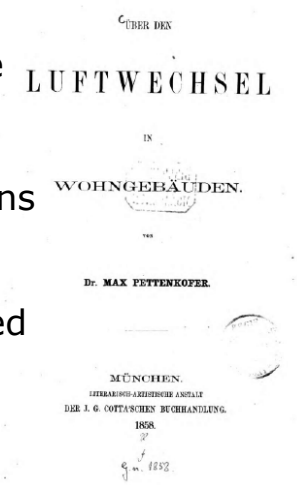
CO_2 % diss. w/ IAQ, performance



Source: Fanger (1988)

Origin of CO_2 as an air quality index

- Water, carbon dioxide and volatile organic compounds are significant metabolic emissions migrating into air
- Besides anthropogenic emissions no other emissions indoors are allowed: other sources than anthropogenic must be removed
- CO_2 is an indicator for (metabolism): exhaled air and other emissions <u>from human metabolism</u>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Dr. MAX PETTENKOFER.

MÜNCHEN.

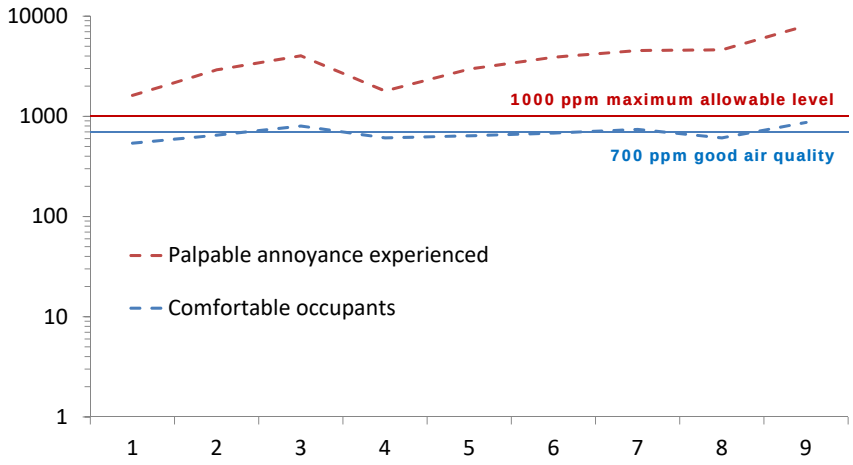
LITERARISCH-ARTISTISCHE ANSTALT

DER J. G. COTTA'SCHEN BUCHHANDLUNG.

1858.

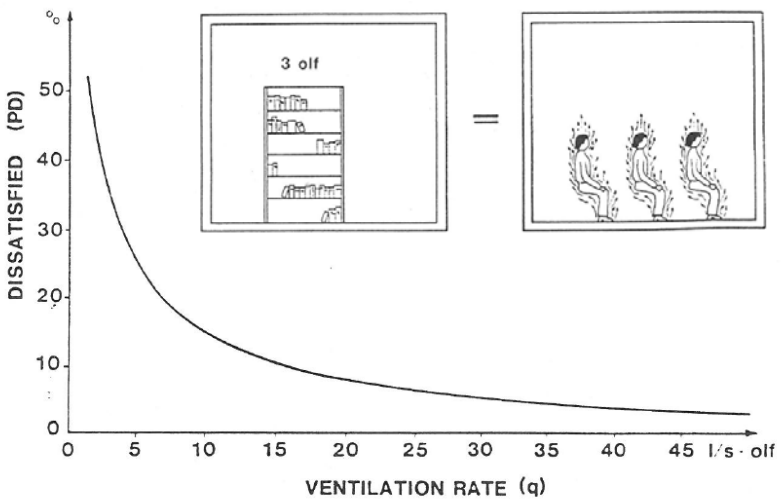
Source: Pettenkofer (1858)

Experimental basis of 1,000 ppm



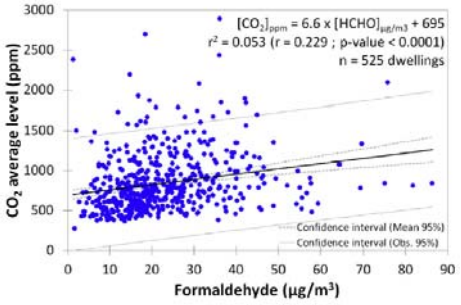
Source: Pettenkofer (1858)

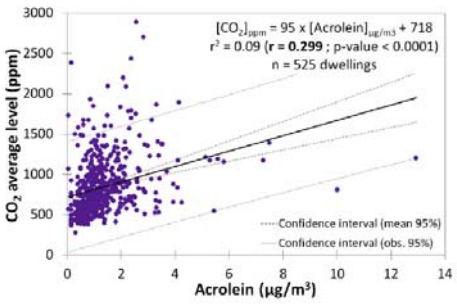
Olf and decipol units



Source: Fanger (1998)

Correlation of CO_2 with indoor pollutants is sometimes positive but weak



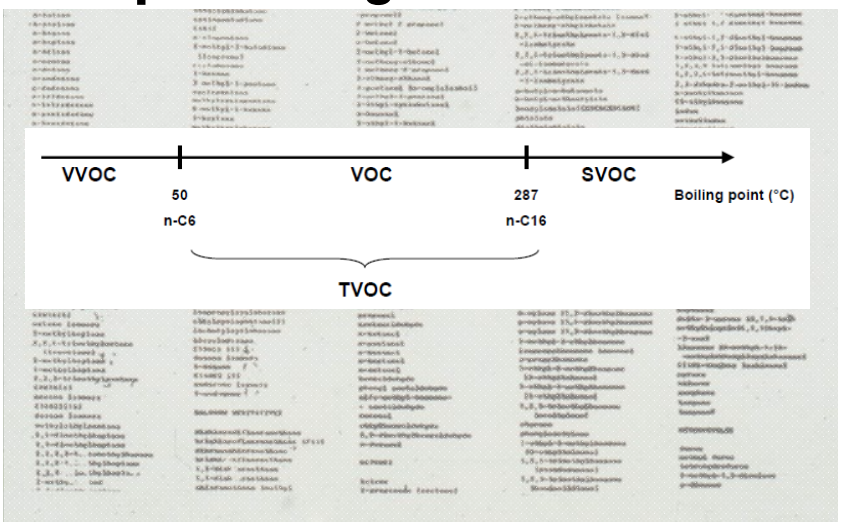


Source: Ramahlo et al. (2015)

Intermediate conclusion, strengths & weaknesses of CO_2

- Time effects, highly variable, often steady state assumed (nearly never reached)
- Requires assumptions regarding generation rates of CO_2 (metabolic rates), which are quite crude and affected by many factors mainly activity but, as recently shown, also thermal discomfort
- Is a marker of ventilation thus contains all pros and cons of ventilation

TVOC
addition of masses of polluting molecules



TVOC dose-response relationships

Total conc. (mg/m³)	Irritation & discomfort	Exposure range
< 0.20	No irritation or discomfort	The comfort range
0.20-3.0	Irritation and discomfort possible if other exposures interact	The range of multifactorial exposures
3-25	Exposure effect & probable headache possible if other exposures interact	The range of discomfort
>25	Headache. Additional neurotoxic effects other than headache may occur	The toxic exposure range

- Based on empirical data (not toxicological evaluations) from field measurements an upper concentration that should not be exceeded is 0.3 mg/m³.
- Apportioned to different classes the upper concentrations are as follows:
  - 0.1 mg/m³ for alkanes
  - 0.05 mg/m³ for aromatics
  - 0.03 mg/m³ for terpenes
  - 0.02 mg/m³ for esters
  - 0.03 mg/m³ for halocarbons
  - 0.02 mg/m³ for carbonyls (-HCHO)
  - 0.05 mg/m³ for others
- Neither of individual compounds should exceed in concentration 50% of average for the class and 10% of the measured TVOC

Source: Mølhave (1991) and Seifert (1990)

Intermediate conclusion TVOC Health & Comfort

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  - 0.05 mg/m³ for others
- Neither of individual compounds should exceed in concentration 50% of average for the class and 10% of the measured TVOC

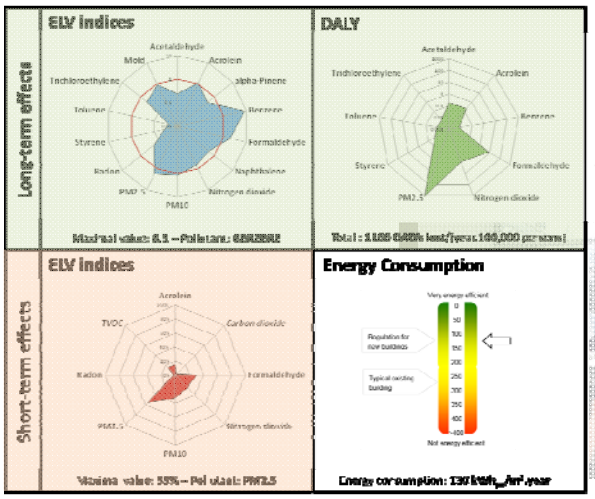
TVOC is not a risk factor for health and comfort in non-ind. environm.

Source: Andersson et al. (1997)

Some other proposed multiple pollutant metrics

- New VOC exposure metrics relative to acute health symptoms reporting based on irritation potency (TenBrinke et al., 1998)
- Indoor pollutant standard index based on CO_2, CO, HCHO, TVOC, PM, bacteria, fungi and thermal comfort (Sekhar et al., 1999)
- Tolerance index (based on established exposure limits) (Hollick and Sangiovanni, 2000)
- Indoor Air Pollution Index (Moschandreas and Sofuoglu, 1999)
- Pollutant grouping: human occupancy, occupant activities, materials and behavior (Mouradian and Boulanger, 2012)

IEA EBC Annex 68 Developing IAQ Index



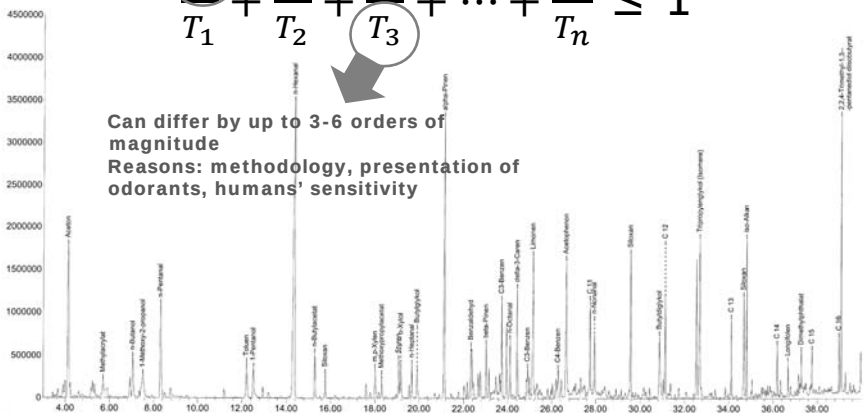
Source: EBC Annex 68 Design and Operational Strategies for High IAQ in Low Energy Buildings (2014-2019)

AIR quality based on ODOR threshold limits

Depends on analytical precision

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \frac{C_3}{T_3} + \cdots + \frac{C_n}{T_n} \leq 1$$

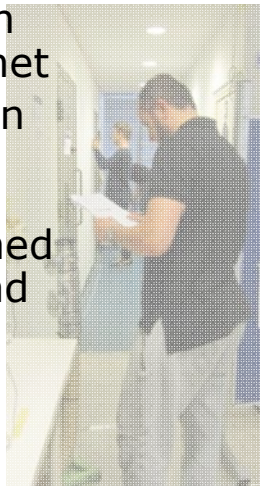
Can differ by up to 3-6 orders of magnitude
Reasons: methodology, presentation of odorants, humans' sensitivity



Source: Devos et al. (1990)

Assessments by humans

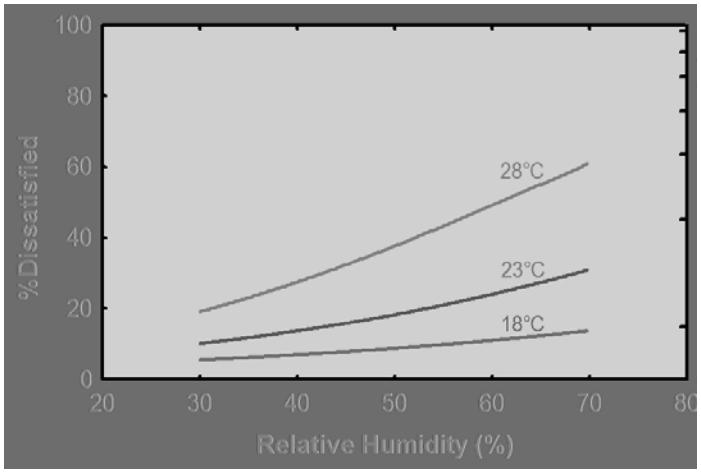
- Quality, the extent to which human requirements are met
- Acceptable air quality: air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction



Factors disturbing precision of subjective ratings of air quality

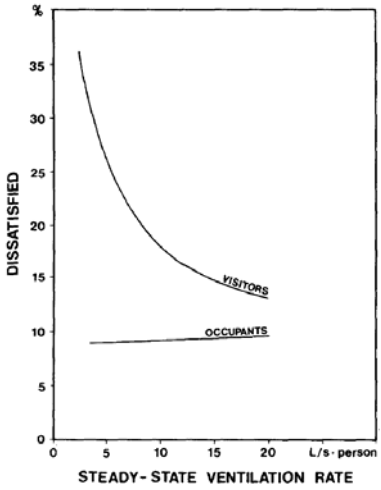
- Type of measuring scale
- Group size (panel) and variation
- Transformation curves
- Endpoints of sensory comfort
- Temperature and relative humidity
- Length of exposure
- Various sensitivity of subjects

Temperature & RH, sensory effects (acceptability)



Source: Fang et al. (1998)

Sensory fatigue (odor not irritation)



Source: Berg-Munch et al. (1986)

Statistical basis for 80 % satisfied

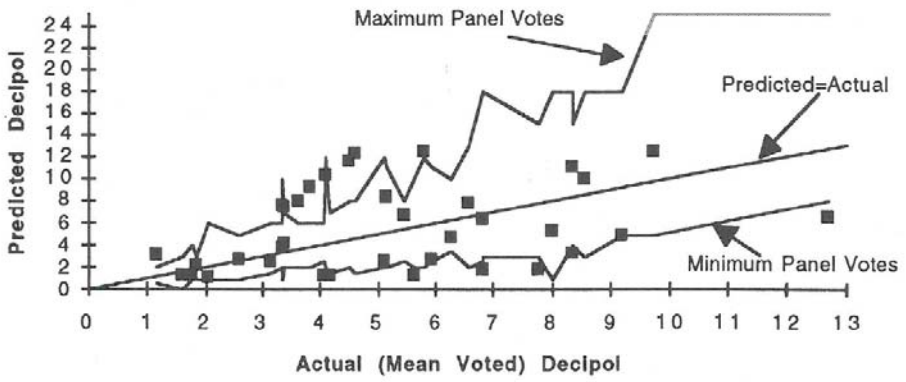
Acceptable ☐

Not acceptable ☐

- Relative standard error (RSE*) ca. 20% for 20 panelists

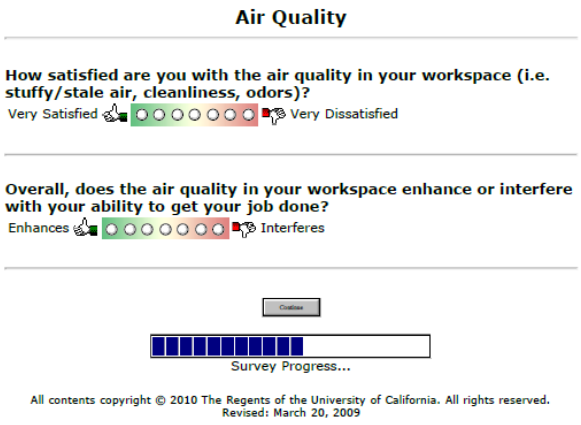
- RSE ca. 10% for ca. 65 panelists
- RSE ca. 1% for ca. 6,000 panelists

Wegner et al. (1993)
The "first" electronic nose?



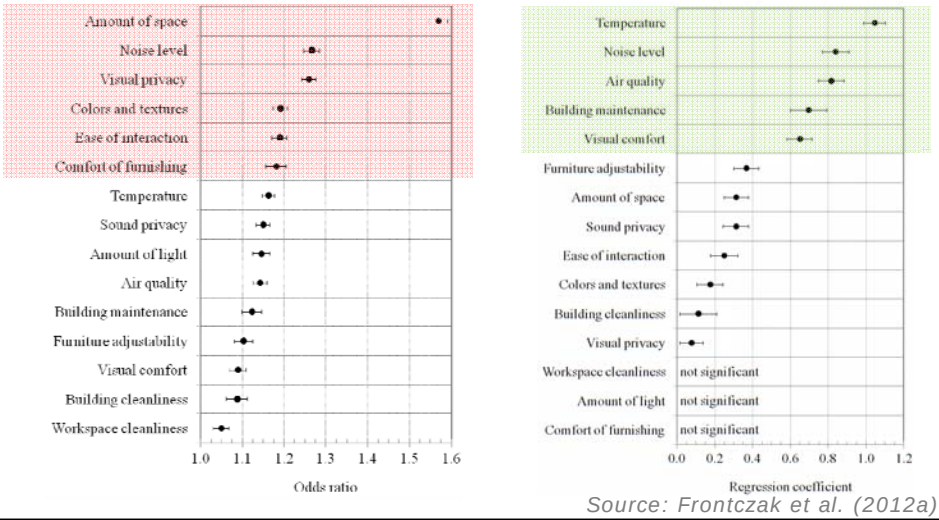
Source: Wegner et al. (1993)

Occupants complaints
Example of questionnaire



Source: CBE Satisfaction Questionnaire

Comfort (satisfaction) with IAQ / IEQ is not the highest priority, for work it is



Source: Frontczak et al. (2012a)

Major limitations of previous attempts

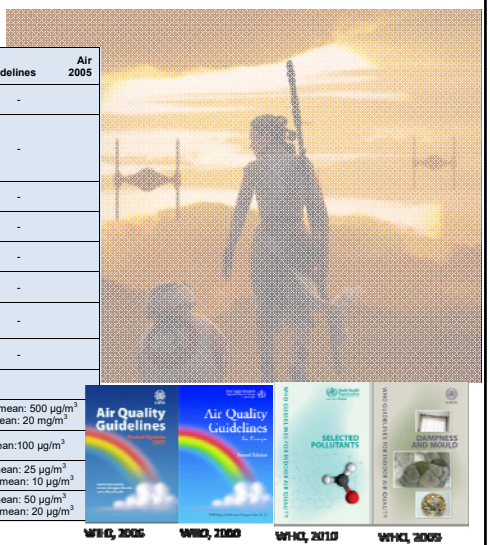
- Address mainly exposures to chemical compounds neglecting other pollutants such as those having microbiological origin
- Address one modality that may not create protection against other impacts
- Arguable reliability and repeatability
- Mostly related to the ventilation compliance

Major challenges

- Incomplete data on the exposures to low-levels of pollutants and their effects on health (acute and chronic), comfort and performance
- Lack of understanding on interactions between pollutants and consequences on humans
- Lack of reference values for many pollutants
- Measurement challenges especially as regards the repeatability, comparability and accuracy
- Time variance of exposure and concentrations
- Huge variation in human susceptibility/sensitivity
- IAQ is not a main attribute of human comfort

Can it be developed?

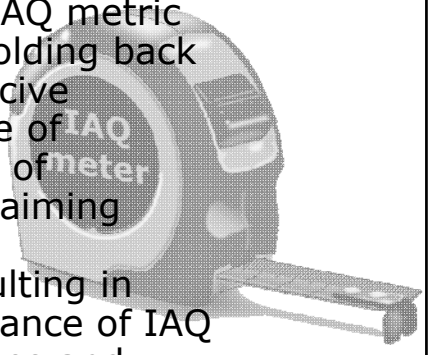
Pollutant	WHO Indoor Air Quality guidelines 2010	WHO Quality guidelines Air 2005
Benzene	No safe level can be determined	-
Carbon monoxide	15 min. mean: 100 mg/m^3 1h mean: 35 mg/m^3 8h mean: 10 mg/m^3 24h mean: 7 mg/m^3	-
Formaldehyde	30 min. mean: 100 µg/m^3	-
Naphthalene	Annual mean: 10 µg/m^3	-
Nitrogen dioxide	1h mean: 200 µg/m^3 Annual mean: 40 mg/m^3	-
Polyaromatic Hydrocarbons (e.g. Benzo Pyrene A B[a]P)	No safe level can be determined	-
Radon	100 Bq/m^2 (sometimes 300 mg/m^3, country-specific)	-
Trichlorethylene	No safe level can be determined	-
Tetrachloroethylene	Annual mean: 250 µg/m^3	
Sulfure dioxide	-	10 min. mean: 500 µg/m^3 24h mean: 20 mg/m^3
Ozone	-	8h mean:100 µg/m^3
Particulate Matter PM 2,5	-	24h mean: 25 µg/m^3 Annual mean: 10 µg/m^3
Particulate Matter PM 10	-	24h mean: 50 µg/m^3 Annual mean: 20 µg/m^3



Source: WHO (2000;2006;2009,2010)

Is it necessary?

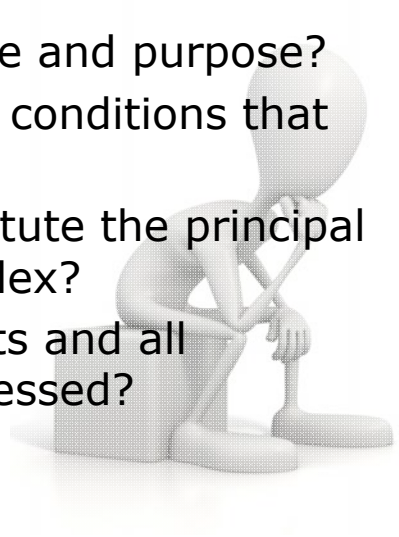
- Lack of IAQ metric or disagreement what should constitute IAQ metric is a significant barrier holding back innovation of IAQ conducive technologies, emergence of undocumented methods of measurements of IAQ claiming their high efficiency and authenticity, this all resulting in undervaluing the importance of IAQ in different credit schemes and compliance metrics related to built environment



Source: Steinemann et al. (2016)

How to advance?

- What is the premise and purpose?
- What are the basic conditions that must be fulfilled?
- What should constitute the principal elements of the index?
- Should all pollutants and all modalities be addressed?



What is the premise?

- Basic human requirements: Indoor air should not compromise the basic human requirements, which include high quality of life, good health and optimal physical and mental activity
- Full spectrum of pollutants
- Use single or multiple criteria/indices

What is the purpose?

- Which human response should be addressed? (health?)
- Voluntary (uptake unknown) or mandatory (political agreement)?
- Used for design (guiding principle) or for operation of buildings (always different from design also for energy)?
- Indicators of unusual (extreme) conditions, cost benefit solutions
- Markers of conditions, indicators of assets, stamps, footprints or labels

Approach?

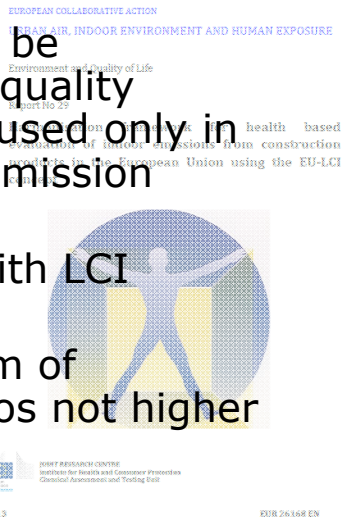
- What are basic requirements?
- Adaptation from already existing indices used by other disciplines
- Using precautionary principle

Minimum requirement: source reduction and elimination

- Sources are ubiquitous
- Sources dominate
- Sources are diverse
- Products purchased and used by people are diverse
- Minimum standardization is needed otherwise no progress will be achieved
- This applies both for commercial and residential building sector

EU-LCI concept
Building Material Labelling

- EU-LCI values are not to be considered as indoor air quality guidelines but are to be used only in the context of material emission testing
- Around 200 pollutants with LCI values
- Risk Index based on sum of concentration to LCI ratios not higher than 1

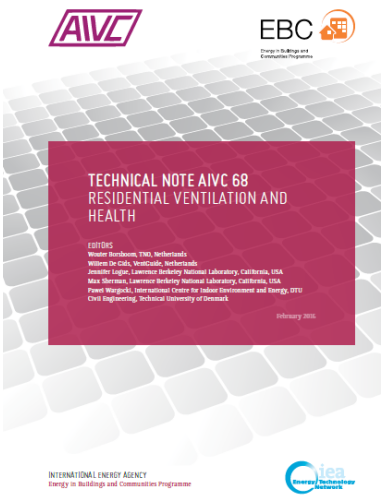


QALY and DALY (and LLY)

- Used by health interventions, based on the burden of disease
- QALY, Quality-Adjusted Life Years is a measure of years lived in perfect health, prospective metric estimating quality of life-years remaining (promotion of health supporting initiatives)
- DALY, Disability Adjusted Life Years, is a measure of years in perfect health lost, retrospective metric estimating consequences (promotion of disease avoidance initiatives)

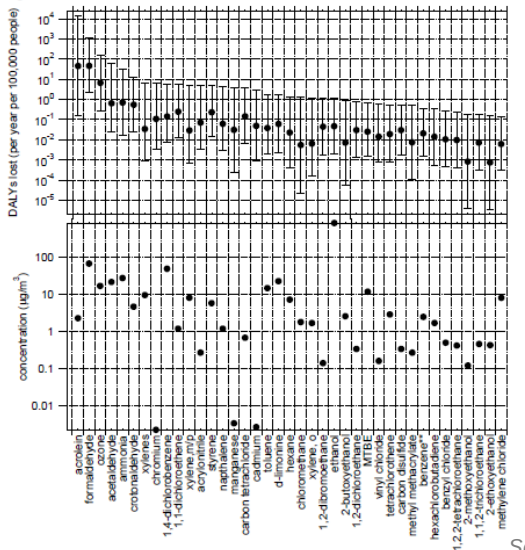
Residential Ventilation and Health

- Summary of measured pollutants, concentrations and associated sources
- Prioritizing indoor pollutants based potential chronic and acute health effects, DALY approach
- Definition of control strategies for identified target pollutants
- 3-tier priority research agenda defined: fundamental research needs (performance criteria), solution-oriented research, and policy needs, management and implementation



Source: AIVC, TN68 (2016)

Pollutants of concern



PM2.5
ACROLEIN
FORMALDEHYDE

Source: Logue et al., EHP (2012)

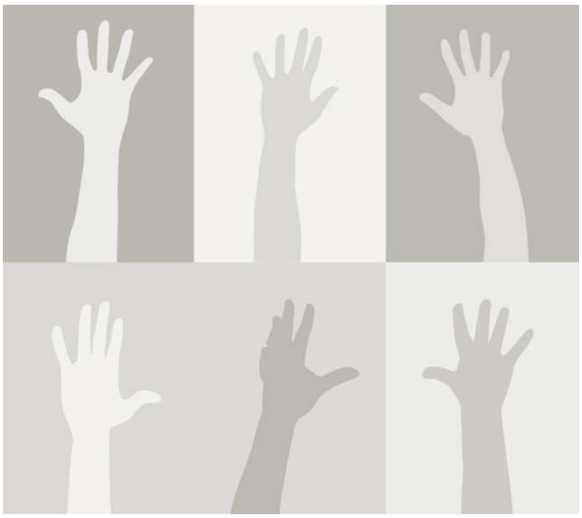
Summary, roadmap (why-what-how)

- Step 1 - WHY: Define the purpose of the metric
  - A stamp of IAQ conditions
  - An alert for building occupants and FM to take some control actions
  - Avoid/minimize negative effect on humans, e.g. pass/not pass
  - Input for control of building systems, e.g. to manage ventilation, air cleaning and filtration
  - Predict/assess the size of effect on humans, e.g. for risk estimation, for setting the level of air quality, for cost-benefit analyses
  - Combination of above
- Step 2 - WHAT: Define the performance/compliance criteria
  - Comfort, e.g. perceived acceptability, odor intensity, satisfaction
  - Health, e.g. acute effects, chronic (toxic) effects
  - Productivity, e.g. effective time at work
  - Combinations of above
  - Agree on treatment of sensitive individuals (MCS, odor, health)
- Step 3 - HOW: Define the markers/indices/pollutants of concern
  - A single or group of contaminants
  - Combined contaminants in a new metric
  - Others

Three prime research initiatives

- Mapping pollutants and responses (traditional approach): Developing IAQ metric based on pollutant data and the advanced IAQ sensor technology integrating Big Data and fitting into the Internet of Things network
- Mapping/monitoring human physiological parameters: Developing Health Performance Indicators using biomarkers or other physiological responses
- Examine efficiency of pragmatic solutions and currently proposed indices

Thank you
Questions and comments



Please contact **paw@byg.dtu.dk** *for additional comments and questions*