Experience with Low-cost (MOS VOC) sensors – response to typical pollution activities and suitability for demand control in residential ventilation

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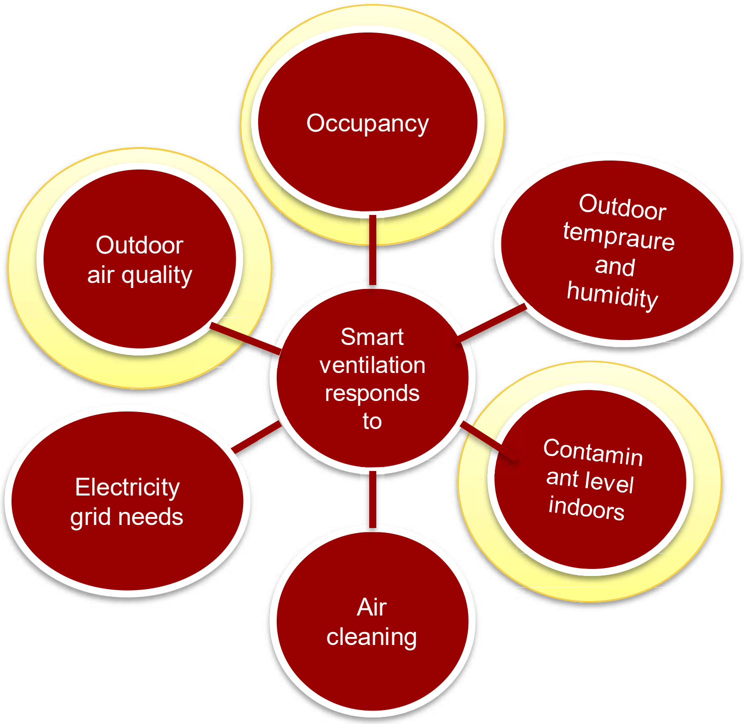
Making ventilation smarter



Figur 1: Based on "Main features of smart ventilation" (Durier et al. 2018)

We need suitable sensors!

- Low price
- Low energy use
- Integration with IoT
- Resilient and reliable
- Stability over time
- …

Possibilities?

- Metal Oxide Semiconductor (MOS)
- Photo Ionization Detector (PID)
- Flame Ionization Detector (FID)

Why Metal Oxide Semiconductor (MOS) VOC sensors?

- Application of MOS VOC sensors seems to be an obvious step towards smart ventilation
- They offer possibility to not only account for pollution related to occupancy, like CO_2 sensors, but also for diverse odorous events taking place in a space
- Moreover the MOS technology allows producing sensor units that are significantly (about three times) cheaper than current non dispersive infrared (NDIR) CO_2 sensors
- Other advantages claimed by producers include small energy consumption, small size and high durability
- This not only makes whole ventilation systems cheaper, but also allows for use of larger amount of sensors – IoT applications

Barriers and disadvantages…

- MOS VOC sensors are non-selective = they react to many pollutants!
- MOS VOC sensors provide relative measurement and “non-selectivity” makes calibration difficult
- Some producers solve this by interpretation of measured signal as so called CO_2 equivalent; Herberger et al. (2010), Burdack-Freitag et al. (2009)
- They are cross-sensitive to water vapour/humidity

Illustration of challenges with MOS VOC sensors

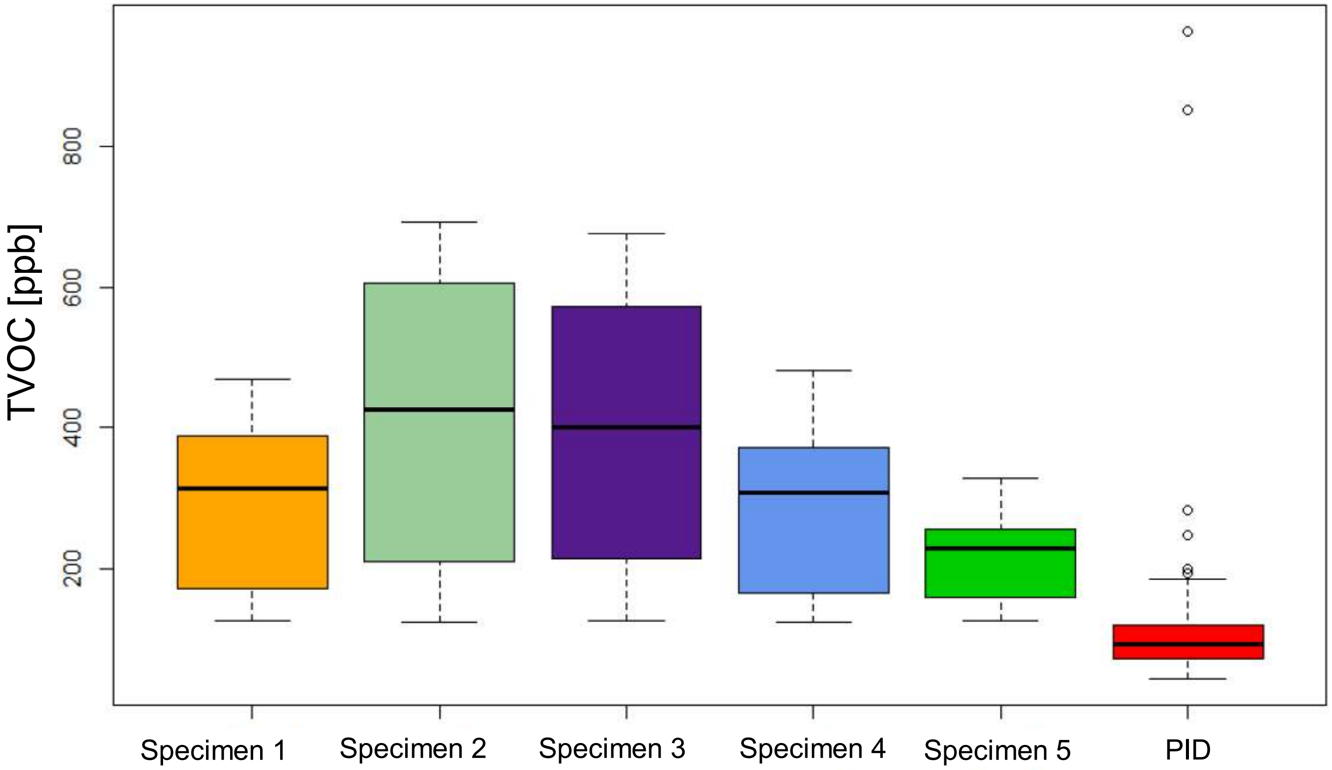


Figure 1: Response of 5 specimen of one MOS VOC sensor integrated in IoT enabled indoor climate monitor (Berg Bojesen 2019)

- Measurements form office environment
- 5 specimen of the same MOS VOC sensor
- Placed side by side
- One week data
- PID measurements for comparison

RoomVent Solutions project

Supported by EUDP

APPROACH & OBJECTIVES

- Study response of commercially available MOS VOC sensors to pollutants emitted during activities typical for residential spaces
- Utilize exposure to residential activities to determine sensor properties:
  Linearity, sensitivity and hysteresis
- Investigate how the data from exposure activities can be used to determine suitability of the particular MOS VOC sensors for Demand Controlled Ventilation

Methods

- 5 MOS VOC Sensors
- 7 activities: cooking, cleaning with detergent, cleaning with dry cloth, linoleum, painting, human bioeffluents, emission of ethanol
- EnergyFlexOffice (EFO) at Danish Technological Institute
  - 7 x 7.5 x 2.6 m, 31.5 m^2
  - Mechanical ventilation, constant air-change ~0.5 h^{-1}
  - Temperature and relative humidity was kept constant at 23 °C and 50% respectively
  - Continuous measurements of VOC by Proton Transfer Reaction-Time Of Flight-Mass Spectrometer (PTR-MS)

Considered sensor properties (under dynamic conditions-activities)

- **Response patterns** for different sensors and activities
  - Absolut response signals
  - Relative response – signal normalized by a background response measured before each activity

- **Characteristic curves** (according to Fahlen et al. (1992)) – sensor response as a function of reference concentration – TVOC determined by PTR-MS measurements

- **Sensitivity**, **Linearity** and **Hysteresis** derived from a linear regression fit to the characteristic curves
  - Sensitivity: slope of the regression fit between reference measurements and response of evaluated sensor
  - Linearity: R^2 of the regression fit
  - Hysteresis: max. difference in the reference and evaluated signals at distinct concentration levels during build up and decay

Sensor response, absolute and normalized

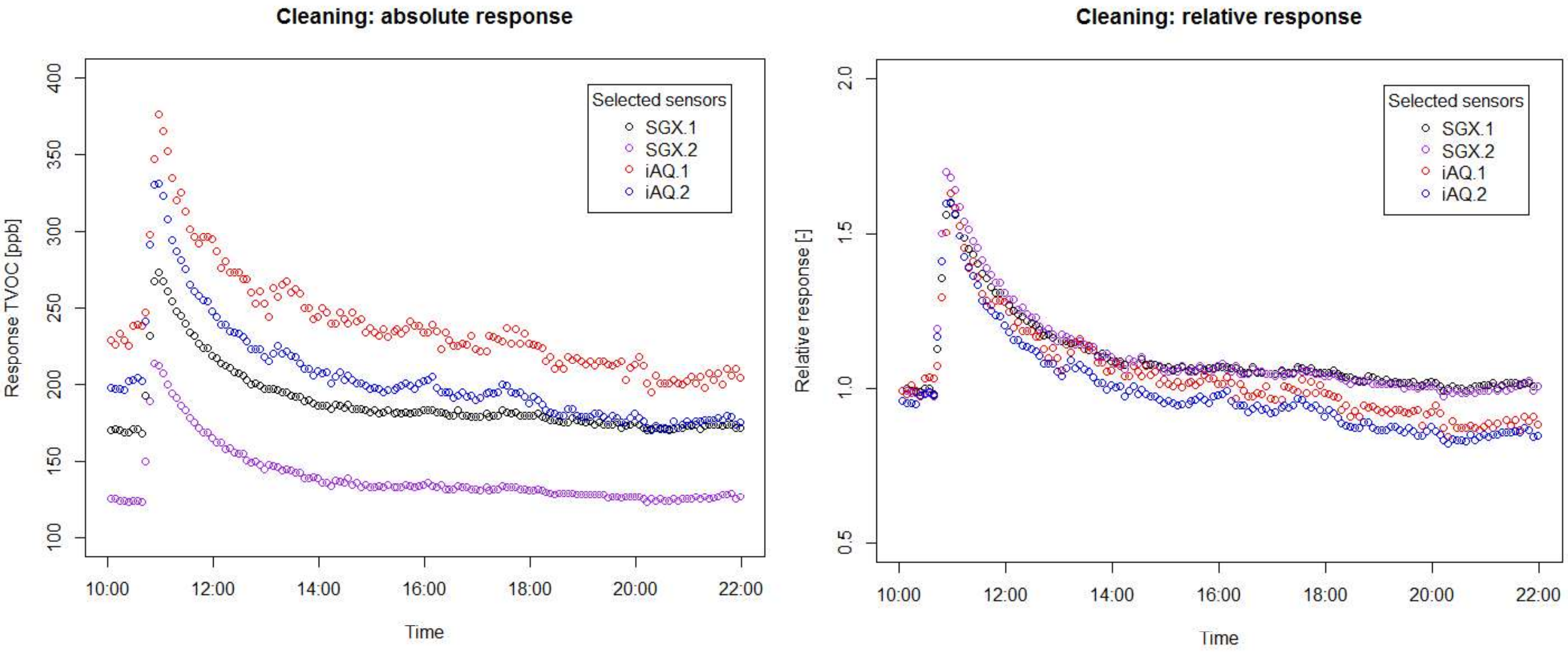
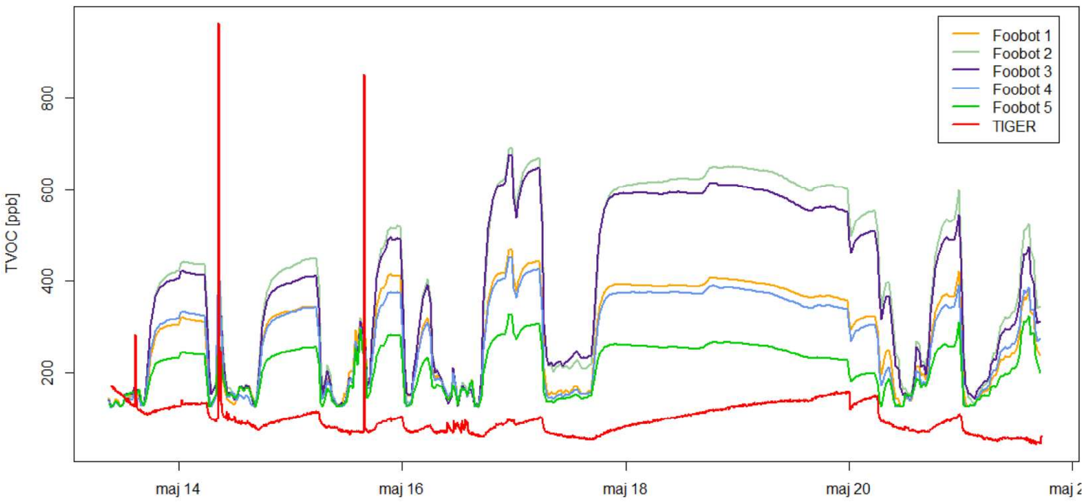


Figure 3: Response of two types of MOS VOC sensors to cleaning with detergent: Left-absolute signal, Right-relative signal normalized by background concentration before activity

- A clear effect of different background concentration on “raw” sensor signal
- Normalized response shows that the sensors reacted comparably

Example from other project

- Measurements from office environment by Berg Bojesen (2019)
- Normalized using so called ”max-min” normalization $x_{i,norm} = \frac{x_i - \min(X)}{\max(X) - \min(X)}$
- Compaison to PID measurement signal (PhoCheck TIGER)



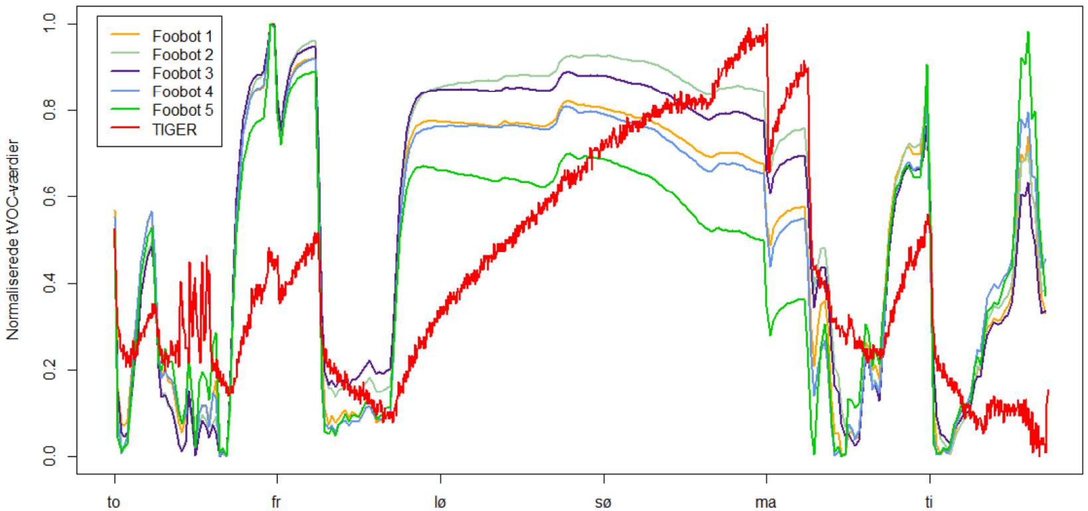


Figure 4: Response of 5 MOS VOC sensors from the same producer to open plan office environment, compared to PID measurement: Left-absolute signal, Right- normalized response

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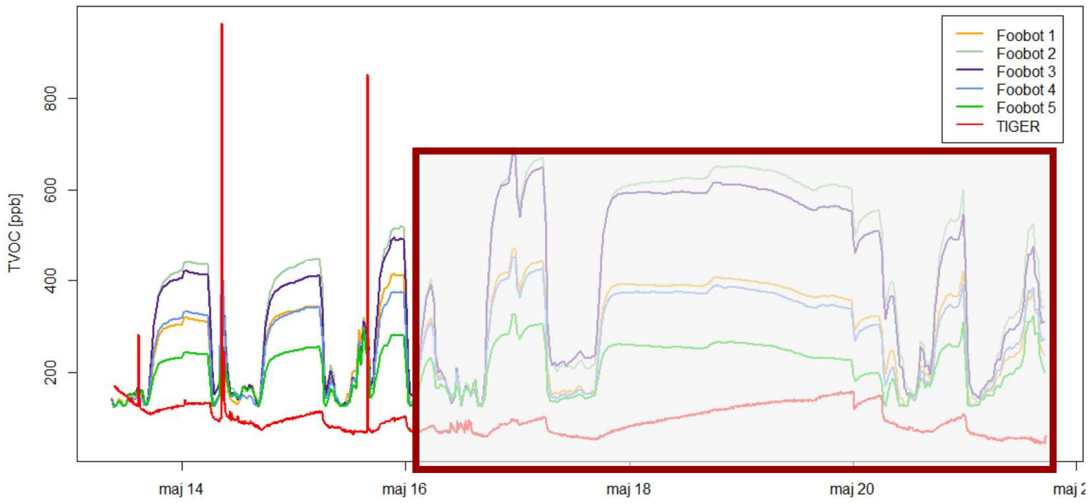

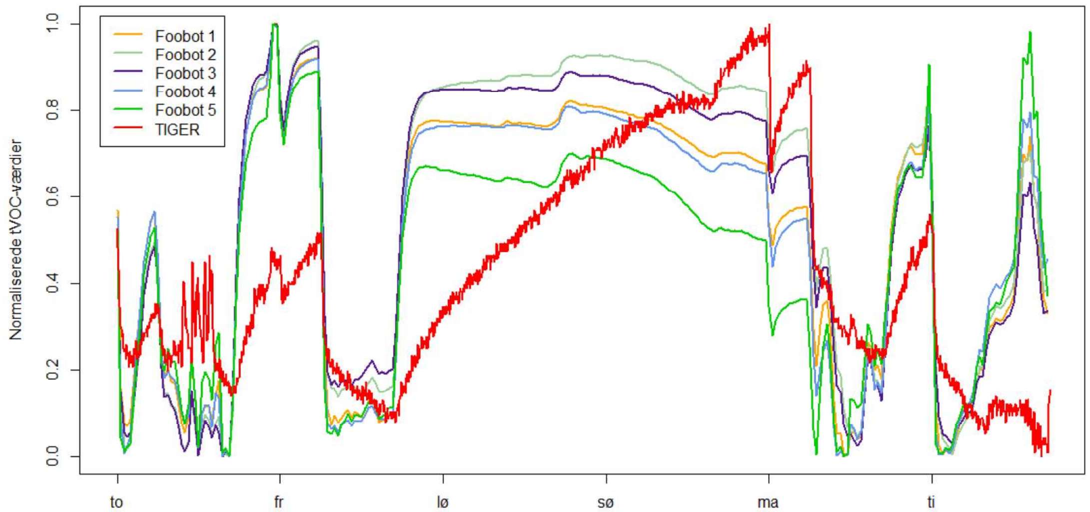

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Response in relation to a reference measurement-Characteristic curve

- Characterization of a response with respect another (preferably more precise) measurement
- TVOC concentration determined by PTR-MS measurements
- Slope of the relationship indicates ”sensitivity” of the MOS VOC sensor
- Characteristic curve uses to determine sensitivity of the sensor under particular condition

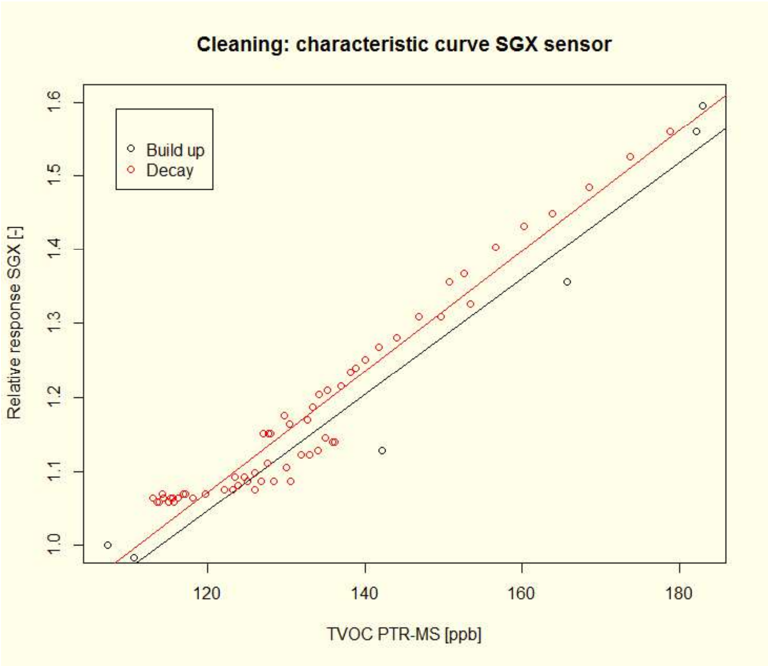


Figure 5: Characteristic curves (build-up and decay) for SGX sensor during cleaning with detergent

“Sensitivity” for different pollution activities in the apartment

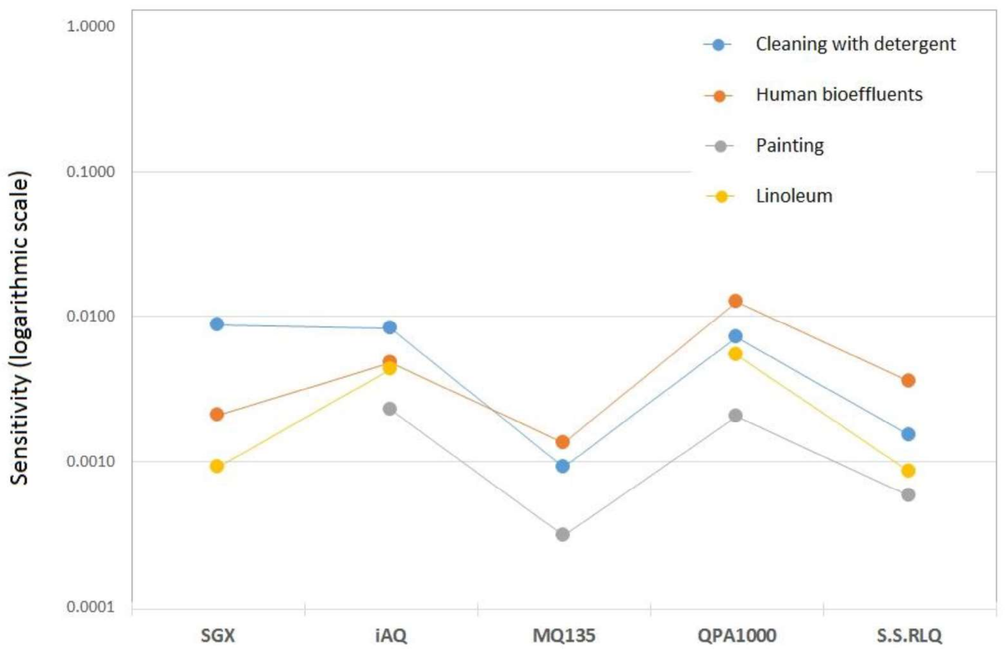
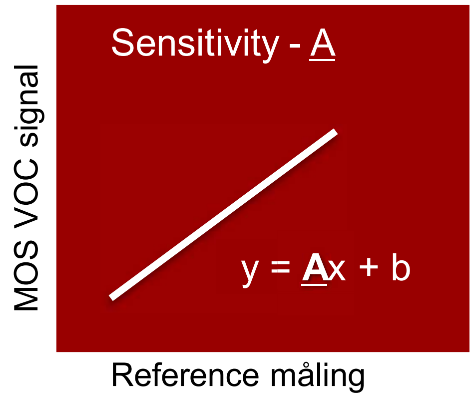


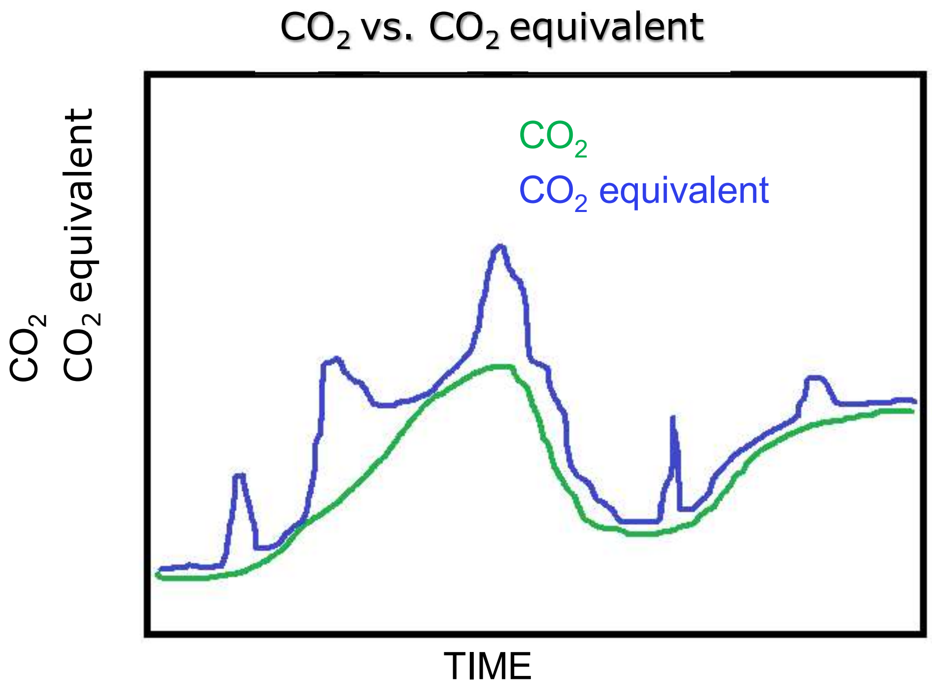
Figure 2: Sensitivity for tested sensor types during exposure to cleaning with detergent, bioeffluents, painting and linoleum



- Sensitivity differs among activities -> probably because the response was driven by different pollutants
- iAQ sensor had most consistent sensitivity
- Sensitivity of SGX, iAQ and QPA1000 during cleaning was comparable

"CO_2 equivalent"

- Calibration of MOS VOC sensor to typical human-emitted VOC (Burdack-Freitag et al. 2009; Herberger et al. 2010)
- "Beyond" CO_2 – measurements of both bioeffluents and pollution from other sources
- Should be easy to understans for users (?)
- Input for ventilaiton control (?)



CO_2 equivalent - reality

- Clear difference between absolute measurement of CO_2 and CO_2 equivalent
- Observed also in a field study by van Holsteijn et al. (2014) in Belgian homes
- Definition of set-punkt is problematic when it should be defined as absolute value – concentration in ppm
- Solution can be using normalized signal or raw TVOC signal instead of the CO_2 equivalent

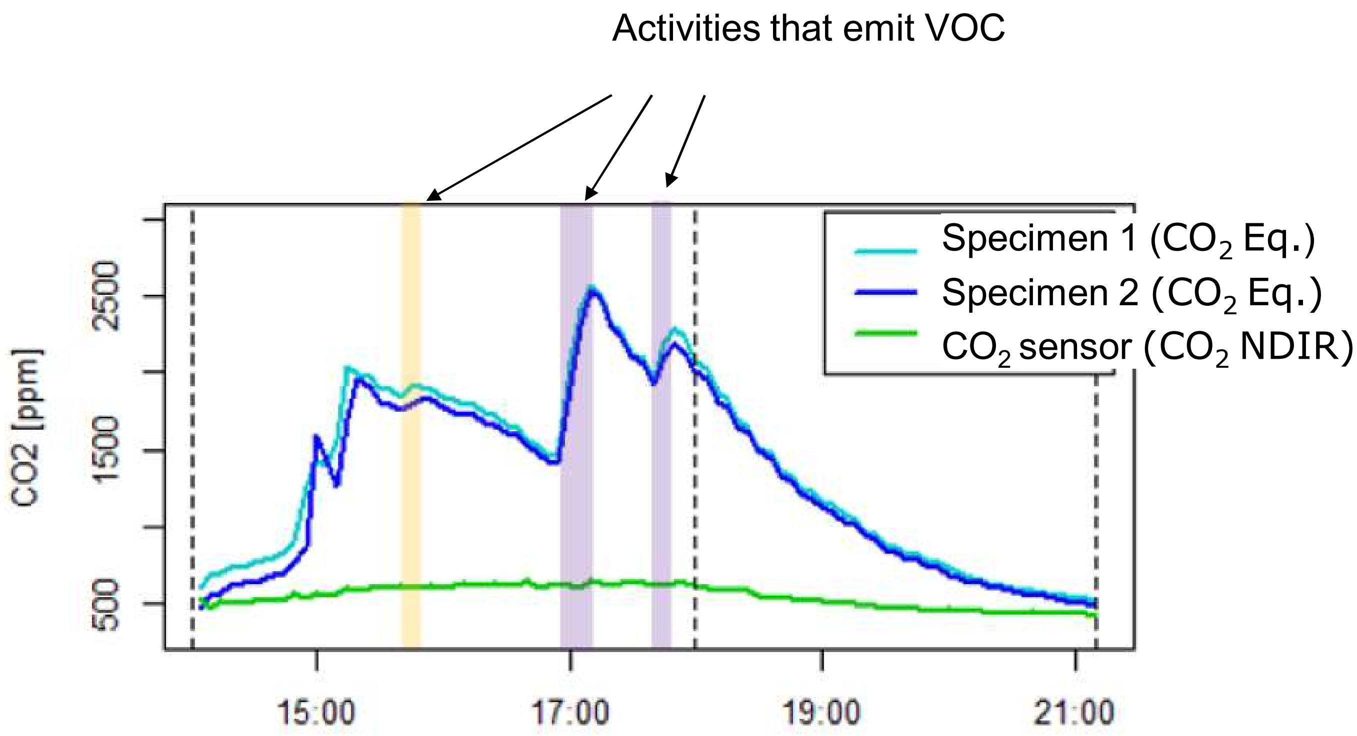


Figure 3: Response-CO_2 equivalent of MOS VOC sensors to typical office work and VOC producing activities (aromatic tea, using whiteboard – writing and cleaning) compared to CO_2 signal measured by NIDR sensor (Berg Bojesen 2019)

Auto calibration

- Auto calibration ensures a ”baseline” concentration corresponding to ”good air-quality”
- Goal is to minimize the disadvantages of relative measurements by MOS VOC sensor
- The assumption is that the lowest concentration corresponds to ”baseline” if it is registred during reasonably long period
- Exact functionality of the algorithm is often proprietary
- Some producers give the user an option to switch auto calibration off

Why can this be a problem?

- It is important to ensure that the ”baseline” represents ”good air-quality”
- An empty building during summer holidays most probably does not have a good air-quality because of emissions from materials, furniture etc. But such response over a long time can result in a shift of the baseline
- Building operation managers should ensure that the MOS VOC sensors are exposed to clean air from time to time, but this is not easy in the practice

Auto calibration - test

- After restart uses Specimen 1 different baseline – baseline has changed
- A difference in absolute concentrations are visible even after > 2 days
- Strong ventilation brings the response of Specimen 2 to the level of Specimen 1

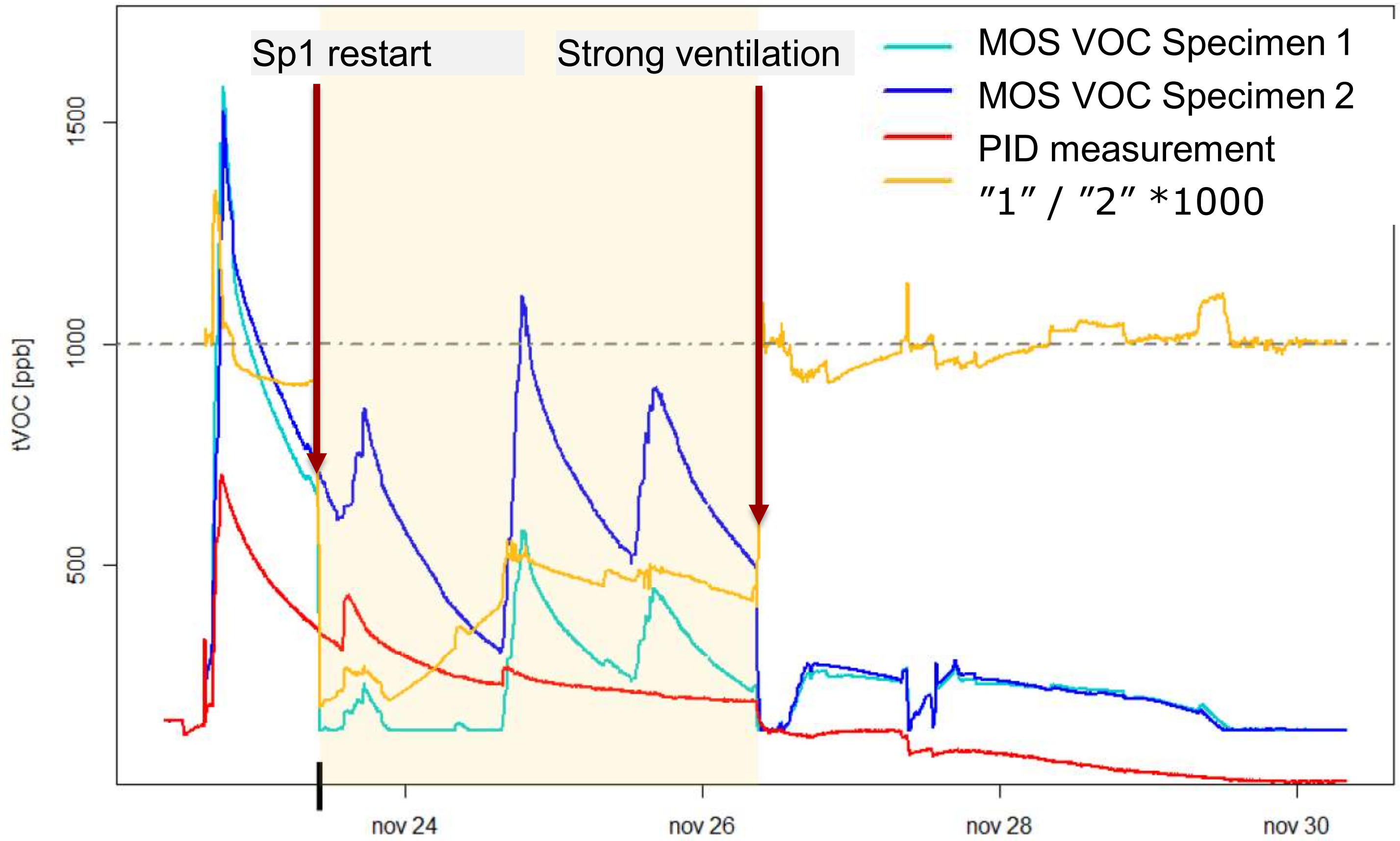


Figure 4: Auto calibration test of two specimen of MOS VOC sensor – yellow area indicates a period between restart of the specimen 1 and application of high air change rate (Berg Bojesen 2019)

Using MOS VOC sensors for ventilation control

- Information regarding sensor properties are often missing
- Relative signal, even several sensors from one producer can present different response to the same conditions
- “Auto-calibration” may be a disadvantage
- Definition of set-point value is problematic due to
  – Broad range sensitivity
  – Relative nature of the response

Definition of set-point?

- Using the same set-points as for CO_2 leads to instabilities and over ventilation (van Holsteijn & Li(2014))

- Definition of response for maximum airflow can be based on a chosen **“reference” activity**

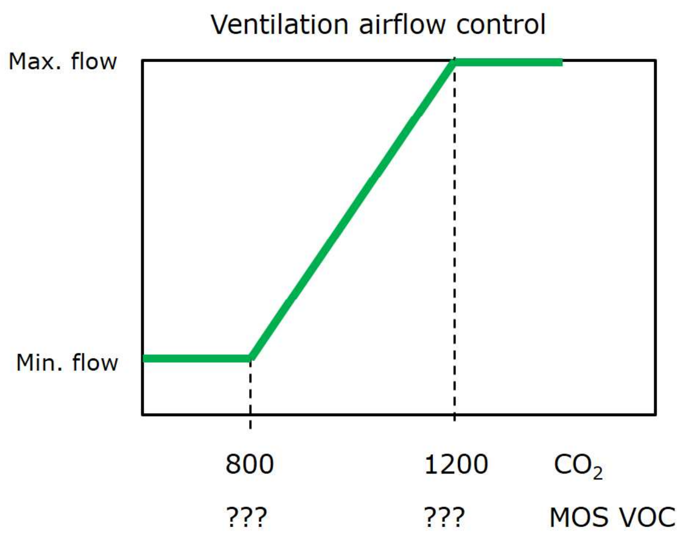


Figure 7: Establishing the set-point/P-band for ventilation airflow control

Example
Using emission of ethanol

- Emission of ethanol represents rather extreme activity
- The choice of reference activity has to correspond with expected usage of the ventilated space

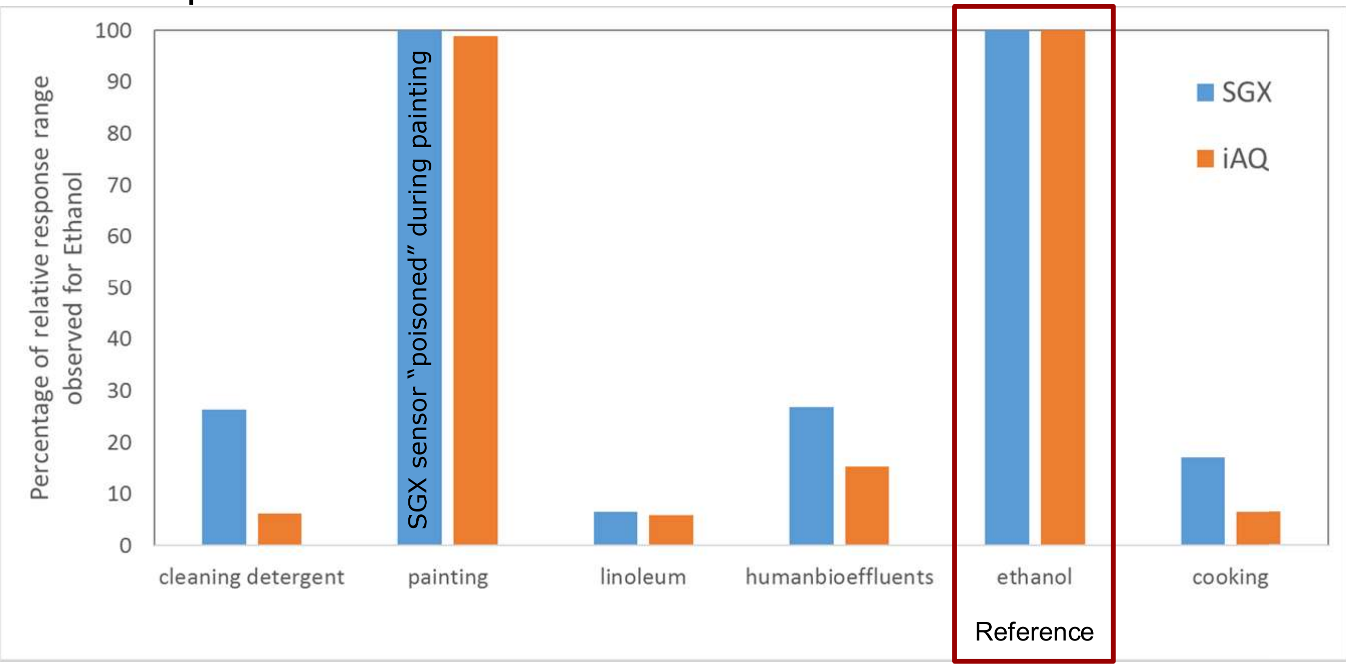
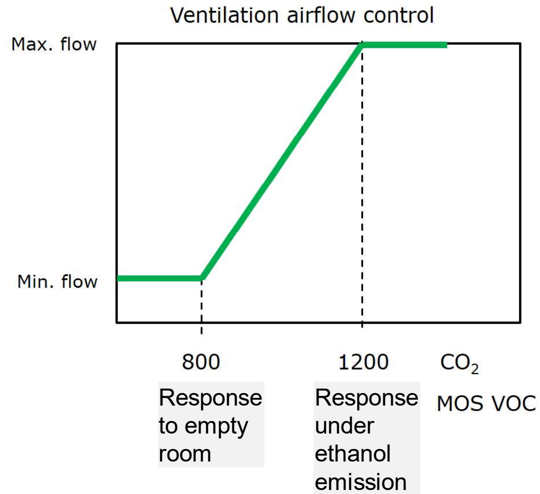


Figure 8: Percentage of relative response calculated based on exposure to Ethanol utilized during other tested activities



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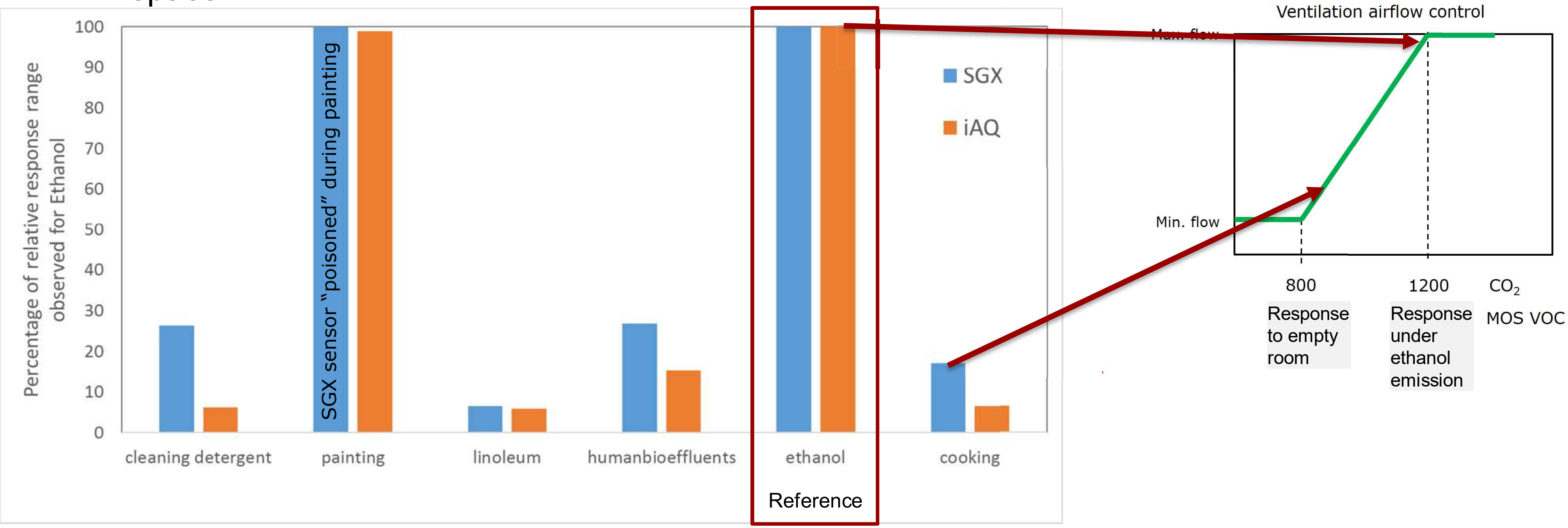

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Summary

- Normalization of the MOS VOC sensor signal gives a possibility for direct comparison of response patterns among different sensors exposed to the same condition.
  – However, normalization does not eliminate the danger of a sensor “auto calibrating” itself to polluted environment

- The experiments showed that the sensitivity of tested sensors differed with respect to particular activities (pollution events)
  – Future work will focus on identification of pollutants that “drive” the sensor response with respect to particular activities

- If “driving” pollutant/s is/aren’t not known, a characteristic activity can be used to determine a relative response change that should correspond to maximum airflow provided by ventilation
  – Aforementioned approach needs to be practically tested in the future

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