Monitoring VOCs' concentrations in a circular biobased residential building using low-cost sensors.

Yannick Thienpont*[1], Seppe Verbiest[1] , Douaa Al Assaad[1], Hilde Breesch[1], Alexis Versele[1]

[1]*KU Leuven, Department of Civil Engineering, Building Physics and Sustainable Design, Ghent Campus, Gebroeders De Smetstraat 1, 9000, Gent, Belgium*

ABSTRACT

Most current building materials are industrially processed, resulting in increased carbon emissions. Global annual carbon emissions due to construction materials reached its peak in 2013, 9.5 gigatons of CO_2 were produced. Upcoming circular economies can have a positive impact on the environment since reusing materials can lower carbon emissions. This economy encourages the use of more innovative materials (e.g., textile insulation, cellulose insulation, hemp, and cork) and recycling old materials. However, there is a lack of knowledge in the literature on the effect these innovative and recyclable materials have on the indoor air quality (IAQ) and human health. Most studies have been conducted in a lab environment and there is a need to monitor IAQ in a real test case study under dynamic indoor and outdoor climatic conditions. The aim of this work was to establish a monitoring campaign of volatile organic compounds (VOCs) in a circular biobased residential building in Belgium using new emerging low-cost VOCs sensors. Given their economic benefits, more sensors can be used covering a wider monitoring area compared to high-end sensors. Measurements were conducted for a trial of two weeks for a case of no ventilation and natural ventilation. Opening of the windows resulted in a large reduction in VOC concentrations, with several sensors measuring values underneath the most stringent threshold value of 300 µg/m³.

KEYWORDS

Indoor air quality, Biobased building materials, Volatile organic compounds, Residential building, Low-cost sensors

1 INTRODUCTION

In Belgium, the concentration of certain indoor pollutants can be higher indoors than outdoors, especially with increasing regulations on envelope air tightness (Hoge Gezondheidsraad, 2017). The modern European citizen spends about 90% of their time indoors, therefore exposure to environmental pollution mainly depends on the indoor air quality (IAQ) (Instituto de engenharia mecanica, 2008; Hoge Gezondheidsraad, 2017; de Kort, 2022). Moreover, nowadays, hybrid working has become more relevant in a lot of companies, so people are more than ever working from home (Van Tran et al., 2020). For this reason, the indoor air of dwellings is a key factor in determining the wellbeing of residents (Hoge Gezondheidsraad, 2017).

Existing pollutants indoors include volatile organic compounds (VOC), and particulate matter (PM) (Van Tran et al., 2020). VOCs are one the main pollutants of building materials, since they are easily vaporized entering the surrounding air (NHBC Foundation, 2009). Common residential building materials, such as wood parquet, gypsum board, PVC coverings, paint etc. are known to shed toxic compounds, such as toluene and formaldehyde (Van Tran et al., 2020). At high concentrations, toluene could cause liver, kidney, and brain damage in case of repeated exposure (New Jersey Departement of Health, 2016) and formaldehyde can cause skin burns and eye damage (National Library of Medicine, 2023). Therefore, materials used for composing the building envelope of new (or renovated) dwellings, should be carefully chosen (Ferreira Pinto Da Silva, 2017).

High performance biobased construction materials, which are produced sustainably and/or using waste products, offer an approach which is environmentally friendly (Keena et al., 2022). However, their effect on the IAQ in actual dwellings are not known. De Kort (2022), conducted laboratory tests on VOC emissions from expanded cork. These experiments showed that after 28 days no exceeded TVOC values were found with the tested expanded cork and the material meets the Belgian level of 1000 µg/m³. However, it should not be concluded that this will universally account for other present and future biobased envelope materials. Moreover, the research conducted thus far has been limited to a small selection of biobased materials under laboratory environments (de Kort, 2022; Maskell et al., 2015; Ferreira Pinto Da Silva, 2017). These studies are conducted under controlled conditions of temperature, solar radiation, RH, etc. while in real life this is not the case. They analyse each material separately and not as a whole working environment, which means that they are not capable to determine the influence of human exposure to indoor VOC concentrations. Therefore, these lab environments are non-representative scenarios. There is a need to monitor VOC emissions of biobased building materials on a real test case residential building with multiple biobased materials present at the same time, influenced by the surrounding environment (temperature, relative humidity (RH), air velocity, etc.).

This paper presents the results of a short-term monitoring campaign, to measure VOC concentrations, in a real circular and biobased residential building using low-cost sensors (LCSs). The emergence of LCSs can help to set up these monitoring campaigns that now rely on very expensive sensors. Due to their low cost, more sensors can be used with the same budget, covering a wider monitoring area. In that way it is also possible to measure differences and compare VOC concentrations between each sensor, in that way spatial trends can be identified. They also have the potential to become effective tools for introducing and engaging students in air quality matters. However, typically LCSs are less accurate and suffer from cross sensitives with other pollutants. Nonetheless, they are still able to provide adequate reliability. Therefore, using low-cost sensing technology for monitoring IAQ must be encouraged. The number of studies with LCSs needs to increase, using them in bigger numbers and over a more extended measurement period. This study provides an overview of the quantitative capabilities of LCSs, using multiple LCSs in a broader environment. It will be one of many studies in which the use of LCSs will become increasingly reliable (Polidori et al., 2017; Alonso et al., 2022).

2 METHODOLOGY

2.1 Case study building: CBCI living lab.

Figure 1: CBCI Living Lab

The CBCI Living Lab project of Interreg was selected for this study. This building is a circular biobased residence which is located at the Technology campus Gent of KU Leuven (Faculteit

Industriële Ingenieurswetenschappen KU Leuven, 2021). The building consists of three floors: a ground floor with toilet, first floor with kitchen and second floor with technical installations. All rooms have a floor area of 20,73 m² and a space volume of 54,88 m³, except the third floor which has a smaller space volume due to the sloping roof. The Living Lab is equipped with a mechanical extract ventilation, denoted as system C in Belgium, which has a standard ventilation rate of 243 m³/h. The air is being extracted on the ground and first floor. During the monitoring campaign, the ventilation system was OFF due to malfunction. **Table 1** shows the materials exposed to the indoor environment.

Table 1: Inner envelope materials and furniture

Source	**Material**
Ceiling	Gypsum board + biobased paint
Wall	Gypsum board + biobased paint
Floor	Pine wood parquet
Furniture	MDF (Medium-density Fibreboard)
Staircase	CLT

2.2 Sensors

2.2.1 Benchmarking test

The low-cost sensors used were the SGP30 sensors of Sensirion (Sensirion, n.d.). To gain insight about the reliability of the LCS, reliability tests were performed in an empty experimental chamber. During this reliability test the LCS measurements were compared to the measurements of a more expensive indoor air sensor (Ethera Nemo). The Ethera Nemo sensor measures linear VOCs, this means less than 4 carbon atoms. The SGP30 sensor measures TVOCs, this is why no similar values were expected, only similar trends. The experimental setup was created to simulate a ventilated room. On one side of the cardboard box a ventilator was placed to have an inlet of air. On the other side of the box another hole was opened, to have an outlet for the inside air.

In **Figure 2** it was clear to see that both sensors followed similar trend. There was a big increase in values measured followed by a gradual reduction visible on both sensors. The SGP30 and the Ethera Nemo both reached their maximum values being 60 000 ppb and 47 000 ppb. The general conclusion of this measurement is that the SGP30 can be used for the intended purpose.

Table 2: Specifications sensors

Sensor	**Price**	**Environmental parameters**	**Range (resolution)**
SGP30 (RS Components Benelux, n.d.)	€ 21,19 (incl. BTW)	TVOC CO_2 eq	0 – 60 000 ppb (6 ppb) 400 – 60 000 ppb (3ppm)
Ethera Nemo (Ethera, 2020)	€ 4 565 (excl. BTW)	Formaldehyde CO_2 LVOC PID Temp RH Pressure	0 – 2 800 ppb (1 ppb) 0 – 5 000 ppm (1 ppm) 30 ppb – 5 ppm (1 ppb) 1 ppb – 50 ppm (1ppb) -55 - +125 °C (0,08 °C) 0 – 95 % (0,08 %) 260 – 1 260 hPa (0,02 hPa)

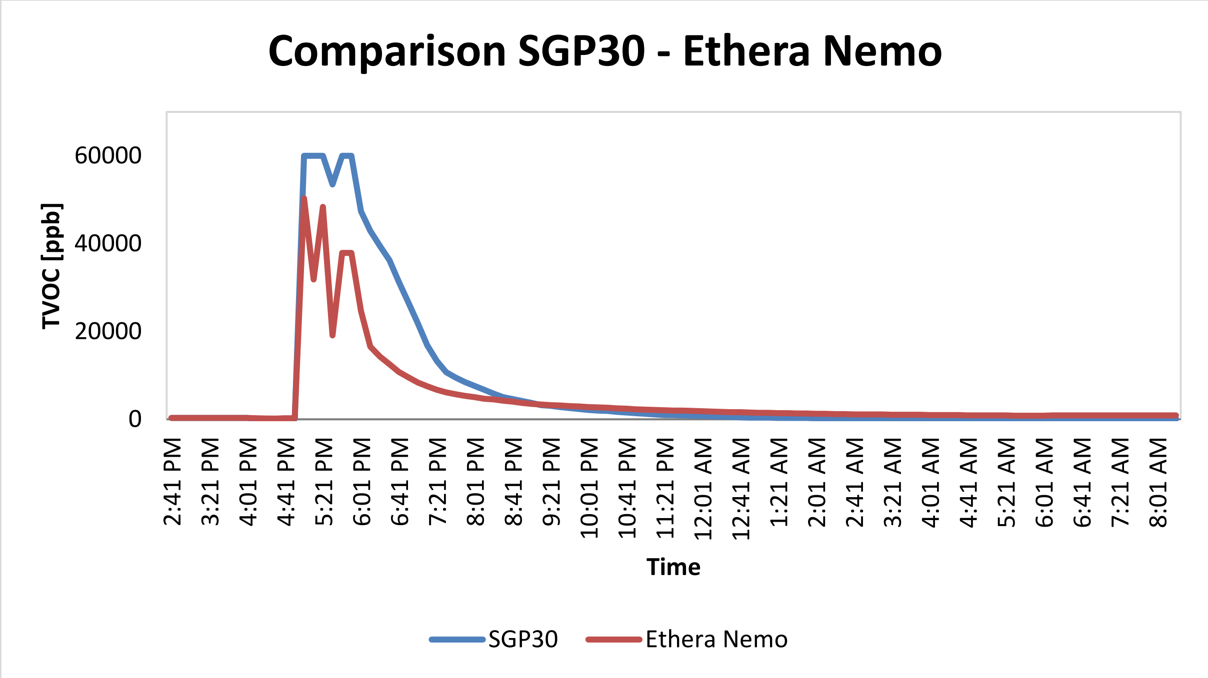

Figure 2: Comparison of SGP30 – Ethera Nemo sensors

2.2.2 Monitoring campaign

During the monitoring campaign, additional to TVOC measurements, temperature and RH were monitored using a HOBO U12 data logger (Onset Computer Corporation, 2008). This is a two-channel logger, which can provide reliable and accurate data since it has an accuracy of +/- 0,35 °C for the temperature and +/-2,5% for RH (Onset Computer Corporation, 2008). This sensor was placed in the centre of the first floor on the kitchen counter.
Multiple SGP30 sensors were placed at 15 cm from the envelope surfaces (floor, wall, and ceiling), see **Figure 3** and **Table 3**. To measure TVOC concentrations of the outdoor air, an additional sensor was placed outside of the CBCI Living Lab.

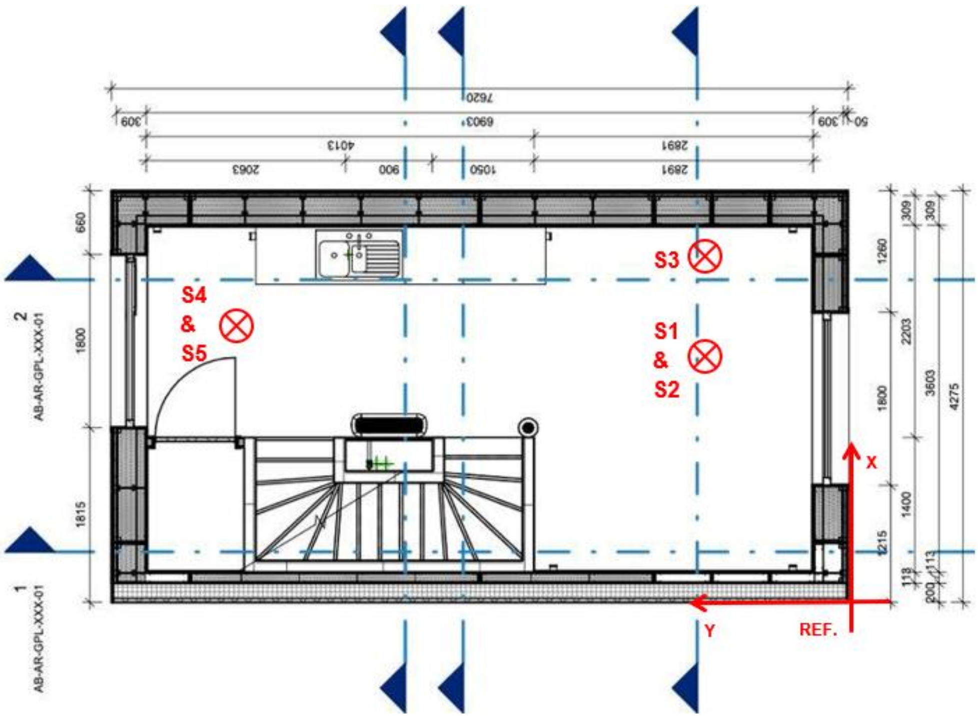

Figure 3: Sensor placement on first floor

Table 3: Sensor placement

Sensor ID	Position relative to reference	Purpose
S1	X: 3m Y: 1m Z: 0,15m [a]	Measuring VOC-concentrations close to floor
S2	X: 3 m Y: 1 m Z: 2,45 m [a]	Measuring VOC-concentrations close to ceiling
S3	X: 3,8 m Y: 1 m Z: 1,3 m [a]	Measuring VOC-concentrations close to wall
S4	X: 3 m Y: 4,3 m Z: 0,15 m [a]	Measuring VOC-concentrations close to floor
S5	X: 3 m Y: 4,3 m Z: 2,45 m [a]	Measuring VOC-concentrations close to ceiling
S6	At bicycle storage 20 m from CBCI	Measuring VOC-concentrations in outside air

[a]: Heights were calculated to be 15 cm from surface. This 15 cm is determined based on two studies. The first one is the study of Huang and Haghighat (2002) where they presented VOC emission with a boundary layer. The intention was to install the sensors outside the boundary layer. The second one is a work of Du et al. (2015), they positioned their sensors 10 cm from the surface. During this monitoring campaign, an extra 5 cm margin was added resulting in the above heights. Ceiling: free height – 15 cm, floor: 15 cm from surface, wall: width – 15 cm and at breathing height.

To find the influence of ventilation, different measuring scenarios were devised, see **Table 4**. To be able to only measure the influence of the building envelope, the building had no occupancy during the measurements. In scenario 2, two windows were opened, one on the first floor and two on the second floor, creating an airflow through the building. The two windows on the second floor were Velux inclined roof windows located on each side. The window on the first floor was a tilt window (**Figure 3**).

Table 4: Scenarios for measurements

Scenario	Details	Duration of scenario
1	Reference case no ventilation	21/03/2023 15:30 – 23/03/2023 8:30
2	Reference case with configuration of open windows	24/03/2023 14:30 – 27/03/2023 7:40

3 RESULTS & DISCUSSION

3.1 Indoor air quality in the CBCI home

The results of the monitoring campaign were analysed based on ppb.hour values. This parameter was used to get an idea to what extent the VOC concentrations of each scenario exceeded the threshold value. According to the Flemish Indoor Air Decree these threshold values amount to a 66.7 ppb target value and 222.2 ppb intervention value (De Brouwere et al., 2022).

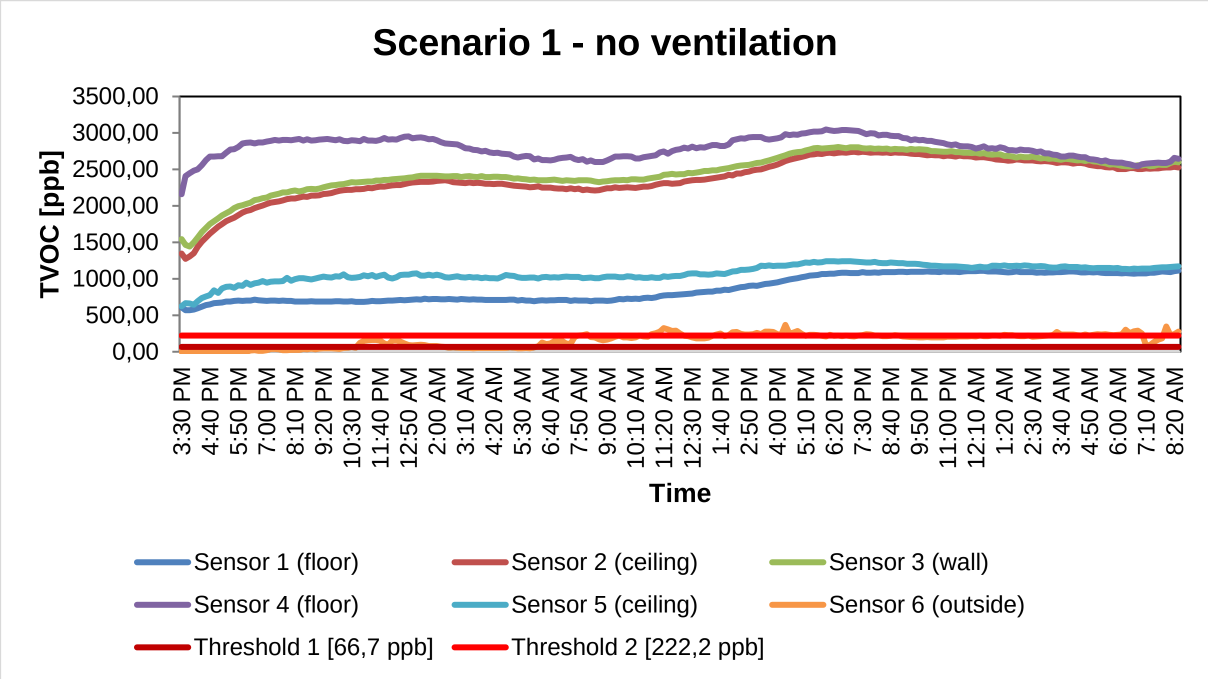

Figure 4: TVOC-measurements during Scenario 1

From **Figure 4,** it can be concluded that each of the five sensors exceeded both threshold values throughout the scenario due to the lack of ventilation and the build-up of VOCs over time. Sensor 4 measuring near the floor had the highest concentrations at an average of 2750 ppb, followed by sensors 2 & 3 (ceiling, wall respectively) at an average of 2250 ppb and finally sensors 1 & 5 (floor, ceiling) at an average of 1000 ppb and 750 ppb respectively. The difference between sensors measuring near the same source can be due to the device-to-device variety, (Sensirion, n.d.). Another reason may be the movement of the air in the room. Du et al. (2015) also showed the difference in air flow rate for different positionings of sensors. The third option is the possibility of a difference of environmental parameters at the different positions of the sensors. As only one sensor was used for temperature and RH during our monitoring campaign, no evidence of this can be provided.

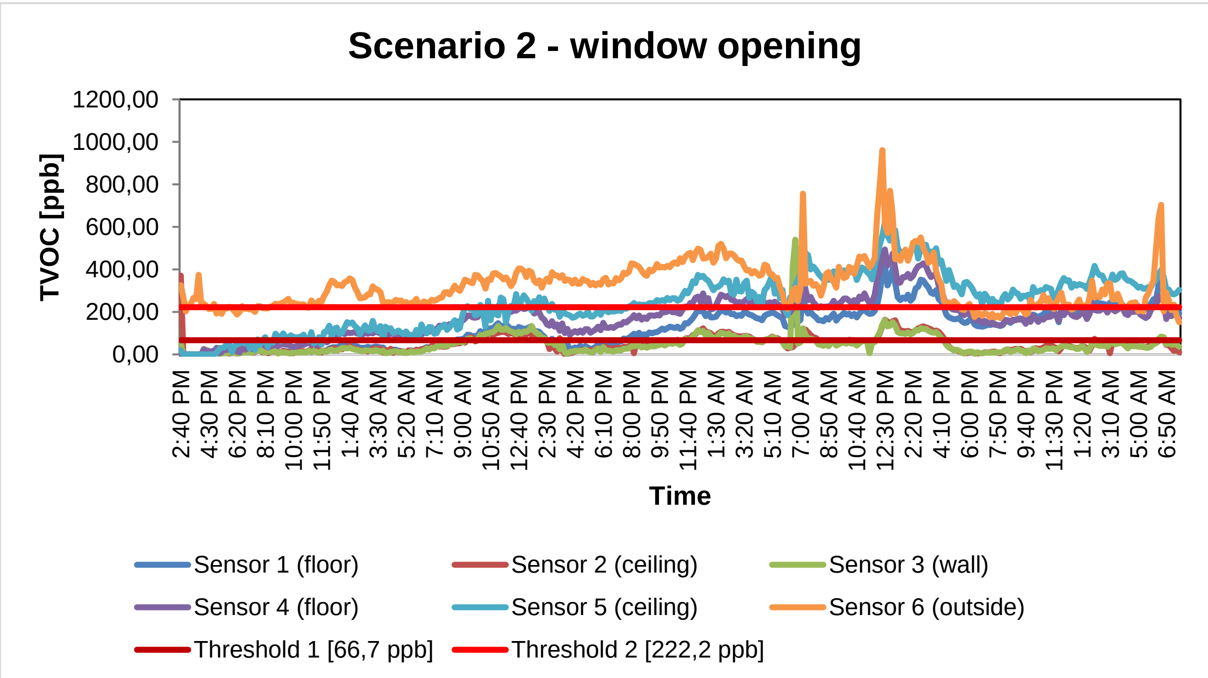

Figure 5: TVOC-measurements during Scenario 2

Opening of windows resulted in reduction of concentrations by 97 % compared to scenario 2a due to favourable wind directions. The lowest threshold limit was not violated for sensor 2 (ceiling) and sensor 3 (wall) throughout most of the scenario. The average values of these sensors were lower than the threshold limit of 66,7 ppb with 48 ppb for sensor 2 and 47 ppb for sensor 3. Sensor 1 (floor), sensor 4 (floor) and sensor 5 (ceiling) were measuring values around the highest threshold limit of 222,2 ppb. With average measurements of respectively 127 ppb, 174 ppb and 246 ppb. Indoor measurements followed the same trend as outdoor concentrations.

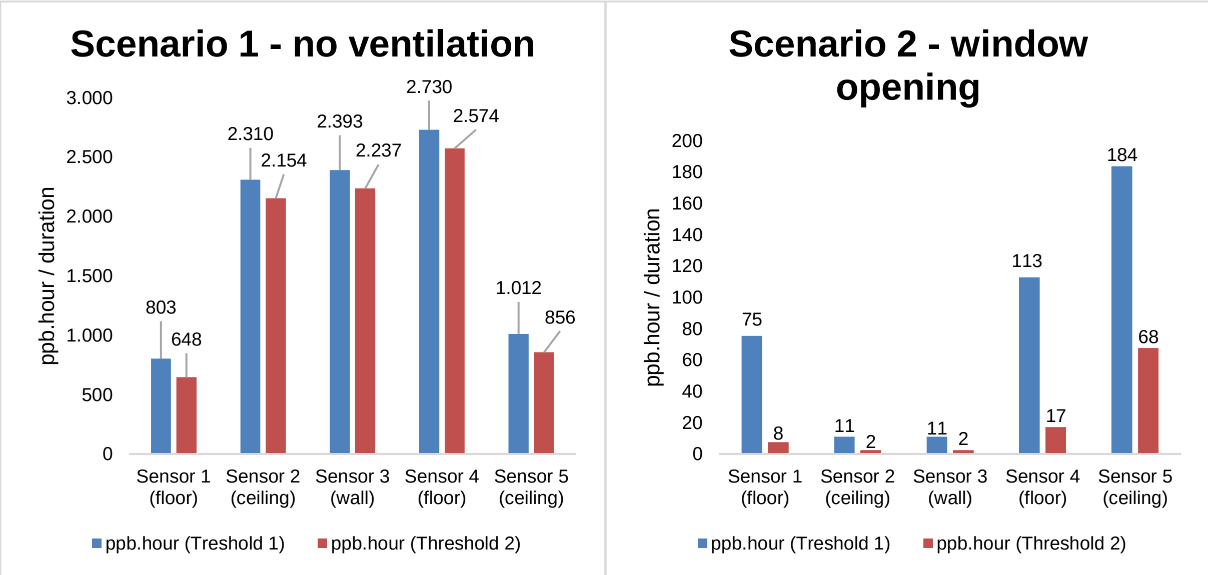

Figure 6: ppb.hour / duration values of Scenario 1 (a) and Scenario 2 (b)

4 CONCLUSIONS

In this study, a short monitoring campaign of VOC concentrations was set-up in a bio-based residential building in Belgium using low-cost sensors (LCS):
The key takeaways can be summarized below:

- In the case of no ventilation TVOC concentrations consistently exceeded both the intervention and target value due to excessive build-up over time.
- Opening of windows reduced the TVOC concentrations considerably. VOC concentrations for sensor 2 (ceiling) and sensor 3 (wall), dropped below the threshold values while it was slightly exceeded for sensor 1 (floor), sensor 4 (floor) and sensor 5 (ceiling).
- Differences in TVOC concentrations can be noticed between the sensors. This is probably due to the device-to-device variety of 25% (Sensirion, n.d.). A difference in air flow rate at each position of the sensor could also be an explanation. There could also be a difference of temperature and RH at each position of the sensors.
- The general conclusion of the reliability measurement is that the SGP30 is usable for the intended purpose. It can be used for a quantification of VOC emission in a case study where biobased materials were used. The trend of the measured values was comparable between the two sensors. This experiment proved that LCS can provide an indication of VOC emission and environmental parameters with a smaller budget. This provides many more opportunities for future work and IAQ monitoring.
- Future work includes benchmarking the obtained values of VOC concentrations in the bio-based home in a regular dwelling with commercial construction materials.

5 REFERENCES

Alonso, M., Madsen, H., Liu, P., Bramming Jørgensen, R., Berg Jørgensen, T., Christiansen, E., Myrvan, O., Bastien, D., Mathisen, H. (2022). Evaluation of low-cost formaldehyde sensors calibration. Building and Environment, 222, 109380. https://doi.org/10.1016/j.buildenv.2022.109380

De Brouwere, K., Bautmans, B., Benoy, S., Geerts, L., Stranger, M., & Van Holderbeke, M. (2022). "Establishing target and intervention guidance values for indoor air in dwellings and publicly accessible buildings: The Flemish approach". International Journal of Hygiene and Environmental Health, 230, 113579. https://doi.org/10.1016/j.ijheh.2020.113579

de Kort, J. (2022). Qualification and quantification of VOC emissions from (biobased) building materials. [Master thesis, Eindhoven University of Technology]. Retrieved January 23, 2023, from https://research.tue.nl/en/studentTheses/qualification-and-quantification-of-voc-emissions-from-biobased-b

Du, Z., Xu, P., Jin, X., & Liu, Q. (2015). Temperature sensor placement optimization for VAV control using CFD–BES co-simulation strategy. Building and Environment, 85, 104- 113. https://doi.org/10.1016/j.buildenv.2014.11.033

Ethera. (2020, January). Ethera Catalogue. Ethera. Retrieved April 15, 2023, from http://www.ethera-labs.com/wp-content/uploads/2020/01/Catalogue_ethera_en_ld.pdf

Faculteit Industriële Ingenieurswetenschappen KU Leuven. (2021, September 02). CBCI Living Lab KU Leuven. KU Keuven Building Physics and Sustainable Design. Retrieved April 02, 2023, from https://iiw.kuleuven.be/onderzoek/building-physics-andsustainable-design/cbci-living-lab-ku-leuven

Ferreira Pinto Da Silva, C.F. (2017). Interactions between volatile organic compounds and natural building materials. [PhD Thesis, University of Bath]. University of Bath. Retrieved March 11, 2023, from https://researchportal.bath.ac.uk/en/studentTheses/interactions-between-volatile-organic-compounds-and-natural-build

Hoge Gezondheidsraad. (2017). Indoor air quality in Belgium. Federal Public Service Health, Food Chain Safety and Environment. Retrieved January 5, 2023, from https://www.health.belgium.be/sites/default/files/uploads/fields/fpshealth_theme_file/h gr_8794_advies_iaq.pdf

Huang, H., & Haghighat, F. (2002). Modelling of volatile organic compounds emission from dry building materials. Building and environment, 37(11), 1127-1138. https://doi.org/10.1016/S0360-1323(01)00089-0

Instituto de engenharia mecanica. (2008, October 31). Co-ordination action on Indoor Air Quality and Health Effects. Cordis EU research results. Retrieved February 21, 2023 from https://cordis.europa.eu/project/id/502671

Keena, N., Raugei, M., Lokko, M., Etman, M., Achnani, V., Reck, B., & Dyson, A. (2022). A Life-Cycle Approach to Investigate the Potential of Novel Biobased Construction Materials toward a Circular Built Environment. Energies, 19(15), 7239. https://doi.org/10.3390/en15197239

Maskell, D., da Silva, C., Mower, K., Rana, C., Dengel, A., Ball, R., Ansell, M., Walker, A., Shea, A. (2015). Properties of bio-based insulation materials and their potential impact on indoor air quality. Academic Journal of Civil Engineering, 33(2), 156-163. https://doi.org/10.26168/icbbm2015.24

National Library of Medicine. (2023, April 08). Formaldehyde. National Library of Medicine. National Center for Biotechnology Information. Retrieved April 09, 2023, from https://pubchem.ncbi.nlm.nih.gov/compound/712

New Jersey Departement of Health. (2016, April). Hazardous substance fact sheet Toluene. NJ Health. Retrieved March 30, 2023, from https://www.nj.gov/health/eoh/rtkweb/documents/fs/1866.pdf

NHBC Foundation. (2009, July). Indoor air quality in highly energy efficient homes – a review. NHBC Foundation. Retrieved March 15, 2023, from https://www.nhbcfoundation.org/wp-content/uploads/2016/05/NF18-Indoor-air-quality-in-highly-energy-efficient-homes.pdf

Onset Computer Corporation. (2008). HOBO® U12 Temp/RH. HOBO. Retrieved April 28, 2023, from https://www.onsetcomp.com/sites/default/files/resources-documents/7660-C%20MAN-U12-011.pdf

Polidori, A., Papapostolou, V., Feenstra, B., & Zhang, H. (2017). Field Evaluation of Low-Cost Air Quality Sensor. Air Quality Sensor Performance Evaluation Center. Retrieved April 28, 2023, from https://www.aqmd.gov/docs/default-source/aq-spec/protocols/sensorsfield-testing-protocol.pdf

Sensirion. (n.d.). SGP30. Sensirion. Retrieved April 20, 2023, from https://sensirion.com/products/catalog/SGP30/

Van Tran, V., Park, D., & Lee, Y.-C. (2020). Indoor Air Pollution, Related Human Diseases, and Recent Trends in the Control and Improvement of Indoor Air Quality. International Journal of Environmental Research and Public Health, 17(8), 2927. https://doi.org/10.3390/ijerph17082927

RS Components Benelux. (n.d.). Seeed Studio Grove-VOC and eCO2 Gas Sensor (SGP30) Gas Sensor for SGP30 Indoor Air Quality Application. RS. Retrieved April 28, 2023, from https://benl.rs-online.com/web/p/sensor-developmenttools/1845085?cm_mmc=BE-PLA-DS3A-_-google-_-PLA_BE_NL_Raspberry_Pi_%26_Arduino_%26_ROCK_%26_Development_Tools_Whoop-_-(BE:Whoop!)+Sensor+Development+Tools-_-1845085&matchtype=&pla338196066953&gclid=Cj0K